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This study has attempted to analyze the benefits and constraints of wastewater aquaculture technology in oreder to provide information and recommendations that may further the development of this technology.

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ABSTRACT

The use of aquaculture as a wastewater treatment technology is a relatively recent development. This study was conducted to assess why aquaculture is not being more widely used to treat industrial, agricultural, and municipal wastewaters. Wastewaters amenable to aquaculture treatment are inventoried and constraints which are limiting to more widespread application of aquaculture technology are assessed. The report concludes that aquaculture is a viable technology which can be used to treat many biologically treatable wastewaters. Potential benefits cannot be fully realized under current regulatory restrictions and technological constraints. The study suggests that wider dissemination of technical information, coordinated efforts to reconsider regulations, and additional research will benefit future applications of this technology.

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CHAPTER 1

INTRODUCTION AND SUMMARY

1.0 INTRODUCTION

Aquaculture can be defined as the mass culture of higher forms of aquatic plants and animals. Under the National Aquaculture Act of 1980 and Draft National Aquaculture Plan (1981), the Federal Government has recognized that there is a substantial potential for providing food, employment, recreation and other values to the public through aquaculture. While the major thrust of this legislation is to encourage aquaculture as a method of farming to produce food and fiber, one of the other values of aquaculture to the public is to provide treatment of certain types of wastewaters and beneficial recycling of wastes. The U.S. Environmental Protection Agency (EPA), under guidance for its municipal treatment works construction grants program (40CFR35.908) has made it policy to encourage and assist in development of aquaculture technology for wastewater treatment.

While far from applicable to all wastewater treatment problems, aquaculture can be an attractive alternative in certain instances to more mechanized, chemical, and energy consumptive conventional treatment processes. Much of the attractiveness of wastewater aquaculture stems from the reliance of such systems on naturally occurring processes to remove pollutants from wastewaters. Whereas the objective of much of current aquaculture technology is to produce a marketable biomass crop, the objective of wastewater aquaculture is to produce clean water. The biomass produced by a wastewater aquaculture facility is only of secondary importance. If the biomass by-products from a wastewater aquaculture facility can be marketed and sold, the revenue can be used to help offset wastewater treatment costs.

Even though the Clean Water Act encourages recycling and beneficial re-use of waste materials, the wastewater treatment and aquaculture industries have only made limited advancement in this area. In keeping with Federal policies and plans to encourage aquaculture, the U.S. EPA has undertaken this study to assess why aquaculture is not being more widely used to treat industrial, agricultural and municipal wastewaters. This assessment had as its major objectives the development of an inventory of wastewaters amenable to aquaculture treatment, and an assessment of the constraints which are limiting to more widespread application of wastewater aquaculture processes as alternatives to conventional wastewater treatment.

This study has attempted to analyze the benefits and constraints of wastewater aquaculture technology in order to provide information and recommendations that may further the development of this technology. In order to assess the current status of wastewater aquaculture, the following questions were addressed:

- What are the various components of wastewater aquaculture systems and what pollutant removal mechanisms can be identified?
- What types of wastewater sources are potentially amenable to aquaculture treatment?
- What geographical and climatological constraints limit the location of particular wastewater aquaculture systems?
- What types of institutional and financial considerations constrain or encourage application of wastewater aquaculture technologies?
- Is there sufficient reliable design information available to engineers for use in designing wastewater aquaculture systems with confidence?
- How do wastewater aquaculture systems compare economically to equivalently performing conventional systems?
- What factors influence by-product harvesting, processing and marketing?

1.1 Summary

This assessment of wastewater aquaculture has led to the following conclusions:

1. Aquaculture treatment processes have been, and continue to be demonstrated capable of secondary, and advanced treatment (nutrient removal) of municipal and certain industrial and agricultural wastewaters.

2. Aquaculture treatment technologies have been applied with a certain degree of success to the treatment of industrial wastewaters such as petroleum refinery wastewater, paper manufacturing wastewater, mine tailings wastewater containing radionuclei, dairy wastes, swine wastes and others. In controlled, experimental environments, aquaculture treatment systems, especially those using aquatic plants, have been demonstrated capable of removing certain refractory organics, heavy metals, and other non-metal elements including boron and arsenic. Aquaculture treatment systems should at least be capable of treating agricultural and industrial wastewaters from sources such as the food processing industry, paper manufacturing industries, beverage industries, meat packing, feedlots and other biologically treatable organic waste sources.

3. Wastewater aquaculture has been demonstrated cost-effective for certain applications. The technology offers potential economic benefits due to low-energy and chemical use compared to conventional treatment processes. While the cost-effectiveness of wastewater aquaculture is not dependent on sale of by-products, it is evident that by-product sale can greatly improve the cost-effectiveness and attractiveness of wastewater aquaculture.

4. The potential economic benefits, however, cannot be fully realized under current Federal and State laws which severely restrict the marketability of wastewater aquaculture by-products. Further demonstration of the safety of wastewater aquaculture by-products from particular types of wastewater is necessary before legal restrictions can be re-evaluated for possible relaxation.

5. There are risks associated with implementation of conventional treatment technologies which stem from design and operational problems. Aquaculture technologies face comparable risks. With proper application of the technology, proper design and proper management wastewater aquaculture can function at least on a par with conventional technologies and in some respects is superior.

6. One of the greatest potential applications of wastewater aquaculture is as a unit process within more conventional process trains to renovate secondary

treated effluent. Wastewater aquaculture has comparatively large land requirements and is a relatively low-energy, naturally based technology. Consequently, the use of wastewater aquaculture treatment probably has its greatest applicability in rural areas.

7. Aquaculture treatment systems are both land and water-based as compared to land treatment systems which is only land based. Consequently, aquaculture treatment systems, in most cases, dictate less of a land requirement compared to land treatment systems. Aquaculture treatment technologies, if properly applied, designed, and managed, can prove to be a cost-effective and viable alternative to land treatment technologies among other innovative/alternative wastewater technologies.

8. While research during the last decade has greatly expanded the state-of-the knowledge about aquaculture treatment systems, in order to optimize performance and gain wider application and acceptance of aquaculture treatment technologies, there are a number of technical constraints which need to be addressed. These research needs include:

   - Development of procedures that can be used by planners and engineers for screening, selecting, and adopting candidate aquatic species for a particular aquaculture treatment problem.
   - Better understanding and quantification of the removal mechanisms and rates of removal which occur in aquaculture treatment systems.
   - Better understanding of the dynamic nature of aquatic process units (APUs) including the effects of environmental or climatic factors on removal mechanisms.
   - The threshold concentrations of various pollutants tolerable by various aquatic species.
   - The optimal environmental conditions for growing various aquatic species, and cost-effective techniques for achieving and maintaining these conditions.
   - Better understanding of various wastewaters and levels of pretreatment requirements prior to treatment in aquatic processing units (APUs).
   - Development of documented procedures for starting up, operating, and maintaining an APU and better understanding of APU controllability and strategies for process control.

- Further documentation of the role of biomass harvesting (criteria, timing, and frequency) for various types of aquatic process units.
- Ability to obtain accurate predictive mathematical models for various types of APUs by considering their dynamic and kinetic characteristics.
- Wider dissemination of available technical information regarding wastewater aquaculture applications, design, construction, operation and associated environmental effects.

If these technological constraints and legal and financial restraints on wastewater aquaculture are removed, then this technology can prove to be a viable alternative to conventional wastewater technologies.

9. The aforementioned constraints can be effectively resolved or eliminated by initiating the following activities:

- Wider dissemination of technical information regarding aquaculture treatment technologies using public media, e.g.; technical seminars; technical conferences; news releases; audio-visual materials; preparation and distribution of planning and design handbooks, documents, manuals, etc.; and publication and distribution of cost data related to aquaculture treatment system design, construction, and management.
- Coordinated efforts among affected Federal agencies including EPA, Department of Commerce, Food and Drug Administration, Department of Agriculture, Department of Interior to examine and revise existing regulations affecting cost-effective applications of wastewater aquaculture technologies with a common objective toward greater beneficial, but controlled, use of wastewater aquaculture products or by-products.
- Sponsorship of research specifically designed to promote better understanding and solutions of the aforementioned technical problems.

CHAPTER 2

WASTEWATER AQUACULTURE POLLUTANT REMOVAL MECHANISMS AND TREATMENT SYSTEM DESCRIPTIONS

2.0 INTRODUCTION

Wastewater aquaculture is a broad category of wastewater treatment methods that use aquatic ecosystems to accomplish wastewater renovation. An aquaculture-based wastewater treatment system may contain a series of aquatic ecosystems or aquatic processing units (APUs)(1) linked together to provide primary, secondary or tertiary treatment, or may combine conventional and aquaculture technologies by using an APU to accomplish a specific objective, for example; nutrient removal. Due to the variety in aquatic species and system alternatives possible in wastewater aquaculture technology, an assessment of why the technology is not more widespread must necessarily include a description of each type of system, and an inventory of wastewater facilities using each type of aquaculture system. The inventory of facilities included in this chapter contains presently operating facilities and identifiable non-operative facilities that were either pilot, demonstration or research-oriented projects, or systems that failed due to various reasons.

Prior to a discussion of the different types of wastewater aquaculture systems, it is necessary to provide a general understanding of the type of treatment and pollutant removal mechanisms characteristic of aquatic treatment systems. Pollutant removal mechanisms active in wastewater aquaculture systems are of particular interest in determining amenability of various wastewaters to treatment, and in the optimal design and operation of aquaculture treatment systems.

2.1 Removal Mechanisms

There are a number of removal mechanisms occurring simultaneously and sequentially in an aquaculture treatment system. The objective of much of the past and on-going aquaculture research and demonstration has been to recognize and quantify these removal mechanisms. The major removal mechanisms include sedimentation, coagulation, adsorption, filtration, precipitation, oxidation, reduction, bacterial metabolism, plant absorption, and animal metabolism. Other removal mechanisms may include ion exchange, extraction, stripping, etc. For a given pollutant, certain removal mechanisms may dominate in an aquaculture treatment system, depending on its design and operation conditions. The mechanisms, by which BOD, suspended solids, nitrogen, phosphorus, heavy metals, refractory organics, and pathogens are removed in aquaculture treatment systems, are discussed in the following sections.

2.1.1 BOD Removal

Biochemical oxygen demands (BOD) in a wastewater generally can be separated into two parts; soluble BOD and suspended BOD. Some of the removal mechanisms for suspended BOD are characteristically different from those for soluble BOD. In an aquaculture treatment system, suspended BOD is first removed primarily by sedimentation, filtration, coagulation, and precipitation and secondarily by absorption through floral and faunal metabolism and catabolism. The suspended BOD is then biodegraded by microorganisms to intermediate metabolites which generally become part of the biomass and soluble BOD within an aquaculture treatment system. The roots and stems of plants in an aquaculture treatment system serve as a filtering and adsorptive media and play an important role in removing suspended BOD.(2) Certain fractions of suspended BOD including bacterial cells and plant material are refractory and become part of the bottom sludge.

Soluble BOD, either originally contained in the wastewater, or present as a result of conversion of suspended BOD, is biologically oxidized first to intermediate substances and eventually to carbon dioxide and water by bacterial enzymatic or metabolic reactions. Portions of the soluble BOD become incorporated into the microbial mass. In an aquaculture treatment system, aerobic bacteria are either suspended in the water column or attached to the roots and stems of aquatic plants, and anaerobic bacteria are generally associated with sludge particles at the bottom sediment. Bacteria attached to plant roots and stems are considered most productive in terms of removal of soluble BOD.

Therefore, the removal mechanisms of suspended and soluble BOD in an aquaculture treatment system are very similar to those in a conventional aerobic or facultative stabilization lagoon. In a conventional aerobic or facultative stabilization lagoon, removal of biomass from the system which is normally in the form of suspended algae, is rather difficult due to smaller particle sizes, and therefore is seldom practiced. In an aquaculture treatment system, removal of biomass (consisting of primarily carbonaceous compounds) can be readily accomplished by harvesting larger sized plants and/or animals. The refractory fraction of the biomass will become part of the bottom sludge and only removed through dredging.

Because of large populations of aquatic species in an aquaculture treatment system, the emission of extracellular organic compounds by plants, excretion of organic waste by aquatic animals, and dissolution of intermediate organic metabolites resulting from biological digestion of bottom sediments cannot be neglected. If growth and accumulation of aquatic species is not controlled by periodic harvest, an aquaculture treatment system may reach an equilibrium state, beyond which BOD removal efficiency approximates leaching of soluble and colloidal BOD. This situation is highly variable and greatly influenced by type of aquatic species used and amount of sludge accumulated in the system. Maintenance of an aquaculture treatment system to contain optimal biomass at a high productivity stage by proper harvest is the key to maximizing BOD removal.

2.1.2 Removal of Suspended Solids

Suspended solids in a wastewater consist of settleable and non-settleable solids. Settleable solids can be removed by sedimentation and filtration in an aquaculture treatment system.

Non-settleable solids, in the colloidal size range, are removed from the water column by attaching to larger particles and plant roots through flocculation and coagulation. Non-colloidal and non-settleable solids are removed by flocculation, coagulation, adsorption, and filtration, and then sedimentation.

Similar to BOD, suspended solids may re-form in pond-type aquaculture treatment systems as a result of (1) algal growth, (2) decay of aquatic plant matter, and (3) growth and die-off of bacterial mass. Floating plant species such as duckweed or water hyacinth, and rooted emergent plant species, such as bulrushes or reeds have been shown to be beneficial in shading the surface of aquaculture treatment ponds and reducing the generation of algal suspended solids. Suspended solids production as a result of aquatic plant decay can be controlled by periodic harvesting. Harvesting may not be practical, however, for certain aquaculture treatment systems, especially those based on natural wetlands.

2.1.3 Removal of Nitrogeneous Compounds

Among the nitrogeneous compounds which are frequently present in wastewaters, ammonia, total Kjeldahl nitrogen (TKN), nitrite, and nitrate are commonly measured as indicators for removal efficiencies of nitrogen in a treatment system. Nitrogen removal mechanisms which occur in an aquaculture treatment system are:

- coagulation and sedimentation of nitrogeneous organic particles;
- biological digestion of organic nitrogen compounds and conversion to ammonia, nitrite, or nitrate;
- conversion of ammonia or TKN materials into nitrate by bacterial nitrification process involving primarily nitrifying aerobes such as nitrosomonas and nitrobacter;
- uptake of nitrate-nitrogen, or in some cases ammonia-nitrogen, by aquatic plants;
- engulfing and metabolism of organic nitrogen particles by aquatic animals;
- conversion of nitrate to nitrogen gas by biological denitrification involving denitrifying bacteria.

- Storage of nitrogeneous refractory materials in the bottom sludge.

The above removal mechanisms are highly dependent on air and water temperature and may practically cease to function during cold weather periods. In general, microbial nitrification and denitrification predominate over other nitrogen removal mechanisms.

Aquatic plants and animals may emit or excrete nitrogeneous compounds such as intermediate metabolites, urea, or nitrogen-containing fecal matter back into the treated water in an aquaculture treatment system. Die-off and decay of dead tissue and bacterial cells can also re-introduce nitrogen loads back into an aquaculture treatment system. It should be noted that nitrogen removal and production mechanisms occur sequentially and simultaneously at varying rates in an aquaculture treatment system. The reaction rates are influenced by type and population of aquatic species, pH, temperature, energy and nitrogen input to the system, and to a lesser extent by the other environmental variables discussed in Chapter 4. Some of the removal mechanisms can be enhanced artificially by construction of greenhouses over the aquaculture systems to maintain temperatures during cold weather months which are more favorable to active growth of aquatic plants and animals. Another artificial enhancement method can be use of thermal effluent to provide heat supplemental to aquaculture treatment systems during low temperature periods.

In summary, the most important method of achieving maximum nitrogen removal efficiency is to maintain an optimal balance of energy (e.g., carbon source, heat, etc.) and nitrogen within a system by proper harvesting of the aquatic plants and animals. Periodic harvest reduces or eliminates net accumulation of dead and living biomass including plant and animal tissues and microbial cells within the system; minimizes breakthrough of nitrogenous compounds; and helps promote maximum nitrogen removal efficiencies. Conventional treatment lagoons usually lack practical harvest mechanisms and breakthrough of nitrogeneous compounds is generally inevitable. This is the characteristic difference between aquaculture treatment systems and conventional treatment lagoons with regard to nitrogen removal.

2.1.4 Removal of Phosphorus

Phosphorus, like nitrogen, is a macro nutrient to aquatic species up to certain concentrations. Aquatic plants can incorporate phosphorus through their metabolic reactions. Typical domestic wastewater and certain industrial wastewaters contain phosphorus in excess of the normal composition of living matter which has a carbon-nitrogen-phosphorus ratio of 100:5:1. For phosphorus-enriched wastewaters, plant and microbial uptake of phosphorus can only account for part of the total phosphorus removal in an aquaculture treatment system and harvesting of aquatic species from an aquaculture treatment system is only one of the removal mechanisms.

Chemical precipitation, coagulation, and sedimentation are believed to account for the majority of phosphorus removal in an aquaculture treatment system. Phosphorus, through chemical interaction becomes part of the bottom sediment. In an aquaculture treatment system, there is an upper limit of phosphorus removal which is established by the solubility of various phosphorus compounds. Once the equilibrium is established, little additional removal of phosphorus can be expected to occur unless the phosphorus-containing bottom sediment is removed. The design life of an aquaculture treatment system relative to phosphorus removal depends on influent phosphorus, the system volume and bottom surface area. The literature indicates that aquaculture treatment systems are similar in phosphorus removal efficiencies to conventional treatment lagoons.

For nutrient-limited receiving water bodies, removal of nitrogen alone from wastewaters before surface discharge may be effective in controlling eutrophication. In these cases, removal of phosphorus from the wastewaters may not be necessary. Otherwise, an aquaculture treatment system should be designed to have ample capacity of phosphorus removal or operated in a fashion so that removal of phosphorus-containing bottom sediments is practical at predetermined intervals.

2.1.5 Removal of Heavy Metals

Heavy metals including radionuclei can be removed by several mechanisms including plant uptake, animal metabolism, chemical precipitation, adsorption, and ion exchange to settleable clay particles and organic compounds. It seems that the latter two mechanisms are most responsible for removal of heavy metals in aquaculture systems. Obviously, sedimentation and filtration play a role in removal of heavy metals after the metals are taken up by the plants and bound by the clay and organic particles.

Colloidal clay particles and organic particles tend to be adsorbed to the plant root systems. Harvesting the whole plant incidentally removes these colloidal particles along with adsorbed heavy metals.

Certain aquatic plants may exhibit preferential metabolic uptake of specific heavy metals.(3,6,7) However, the extent of heavy metal removal by plant uptake in aquaculture systems is not well-documented. Aquatic animals such as oysters, clams or various filter-feeding fish may ingest certain heavy metals (e.g. mercury, chromium, copper, cadmium, etc.) and show accumulations in body tissues in concentrations several times that of the metal concentration in the water column. When the equilibrium state is reached, heavy metals end up partly in biological tissues, partly in bottom sludge, and partly in effluent.

2.1.6 Removal of Refractory Organics

Refractory organic compounds are not easily biodegraded in a conventional biological treatment system, and such systems cannot efficiently remove refractory organic compounds. Aquaculture treatment systems, due to characteristically different biochemical and enzymatic conditions, and long hydraulic detention times, may be effective in removal of refractory organic compounds. Plant uptake, microbial enzymatic reactions, absorption, and adsorption are believed to be major mechanisms responsible for removal of refractory organic compounds from the water column. Among these mechanisms, microbial metabolism and enzymatic breakdown are considered to be the predominant removal mechanisms. These mechanisms also occur in conventional treatment lagoons but reactions occur at slower rates than in an aquaculture treatment system.

2.1.7 Removal of Bacteria and Viruses

Aquaculture treatment systems have been shown to provide removal of enteric bacteria and pathogenic viruses. Similar to conventional treatment lagoons, the bacterial and viral removals in an aquaculture treatment system are attributable to natural die-off accompanying long residence times and the hostile environmental (biological, physical, and chemical) conditions for such organisms which prevail in an aquaculture treatment system.(2)

The lack of warm-blooded host sites hinders the survival of these enteric bacteria and pathogenic viruses. In addition, certain enzymatic intermediates emitted by aquatic plants and microorganisms may create a biochemical environment hostile to the survival of certain enteric bacteria and pathogenic viruses.(2) The extent of pathogen reduction by aquaculture treatment systems, like conventional treatment lagoons, has not been shown to be consistent.

2.1.8 Removal of Trace Contaminants by Aquaculture Treatment Systems

Most of the published research on aquaculture treatment systems reviewed during this assessment emphasized removal of conventional pollutants (i.e. BOD, TSS and nutrients like nitrogen and phosphorus). Relatively few studies have evaluated aquaculture treatment systems for potential removal of trace contaminants (e.g., refractory organics, heavy metals, pesticides, etc.) from either municipal or industrial wastewaters.

McDonald(3) used water hyacinth, alligator weed (Alternanthera philoxeroides), reeds, and cattail for decontamination of radioactive water. Plants were grown in a greenhouse at an air temperature range between 15°C and 31°C. Cesium (Cs), strontium (Sr), and cobalt (Co) were used as indicators for uptake of radioactive substances by aquatic plants. At the end of a four week study, plants were recovered, digested, and analyzed for Cs, Sr, and Co. The study results demonstrated the ability of actively growing aquatic plants to decontaminate radioactive water. In general, bio-concentration by these aquatic plants indicated reductions in volume of contamination by 98.8 percent for reeds, water hyacinth, alligatorweed, and cattails for the indicator radioactive elements tested.

Wolverton and McKown(4) studied the removal of phenol by water hyacinth using a bench-scale system and found that phenol concentrations were nearly undetectable after 48 to 72 hours of detention in the treatment systems. Phenol removal by bacteria on the plant roots was not confirmed and extracts from the water hyacinth biomass did not contain detectable amounts of phenol. It was postulated that phenol was, however, removed by the water hyacinth and primarily metabolized to other compounds through enzymatic perioxidases and phenol oxidases present in the water hyacinth.

A combination anaerobic filter/vascular aquatic plant system was developed and tested by Wolverton and McDonald(5) for removal of phenol and M-cresol from contaminated river water. The common reed (Phragmites communis) and cattail (Typha latifolia) were grown on top of two separate anaerobic filters. The reed and the cattail systems were reported to remove 93 percent and 83 percent, respectively, from 100 mg/l phenol solutions. A plant-free control system showed 60 percent removal at a detention time of 24 hours. The reed system removed 69 percent of M-cresol from 100 mg/l solutions and reed free control system removed 58 percent after 24 hours of detention. It was observed that the phenol and M-cresol were rapidly adsorbed on the filter media surfaces and either assimilated and/or metabolized.

In Louisiana, Tridech and Englande(6)(7) studied the removal of both conventional pollutants and U.S. EPA designated priority pollutants by various aquatic plants. The study was conducted in three phases: field screening, batch screening experiments, and continuous flow. Nine aquatic species including duckweed, coontail, elodea, waterbonnet, alligatorweed, water hyacinth, arrowhead, bulrush, and rush were tested.

In the field screening phase of the study, the concentration of trace contaminants in plant tissue, and the accumulation factor (ratio of dry weight pollutant concentration in plant tissue to pollutant concentration in the water or sediment column) were analyzed. The results indicated that plant tissue concentrations could range from hundreds to thousands of times that of the corresponding water or sediment concentration. This bio-accumulating capability indicates that removal of trace contaminants from wastewater by aquaculture is possible.

In the batch-screening tests,(6,7) secondary effluent from a trickling filter treatment plant was used to acclimatize mature aquatic plants. Influent to the test aquariums was spiked with 1 mg/l of arsenic, 5 mg/l of boron, 1 mg/l of cadmium, 1 mg/l of mercury, 1 mg/l of selenium, 1 mg/l of phenol, and 0.03 mg/l of polychlorinated biphenols (PCB-Arochlor 1254). All experiments were conducted in a greenhouse under temperature conditions of 21 to 23°C. Each batch run was terminated at day 28. Results, given in Table 2.1 demonstrated that, in general, aquatic plant systems were effective in removing cadmium, mercury, phenol, and PCB's; exhibited some removal of boron; but showed little removal of arsenic and selenium, except bulrush and rush. The systems were effective in converting ammonia and removing total nitrogen, but less effective in removal of phosphate. Phosphate removal seemed to be limited by availability of nitrogen. Similar to other aquatic processing units, the experiments showed effective removal of BOD_5 and TOC, especially for rooted plants such as bulrush, rush, and arrowhead, and submerged alligatorweed.

With the aid of kinetic models, Englande and Tridech were able to determine a series of kinetic coefficients for various aquatic plants. These kinetic coefficients are most important in designing aquatic processing units for removal of trace contaminants. The same technical approach can be applied to removal of conventional pollutants (BOD_5, TOC, TSS, ammonia nitrogen, total nitrogen, etc.) provided that the test environmental conditions are conducive for plant growth and do not impose phytotoxicity problems. Since the kinetic studies were conducted in a controlled temperature environment, and since biological and chemical reactions are influenced by ambient air and water temperatures, the effects of temperature on these kinetic coefficients remains to be explored and determined prior to actual design applications. In addition, the threshold values of various trace contaminants, beyond which significant phytotoxicity occurs, needs to be determined for the various candidate aquatic plant species for wastewater aquaculture. Nonetheless, this approach to determining rate coefficients represents a significant advancement in understanding the removal mechanisms involved in an aquatic process unit, which hopefully will lead to better selection and design of future aquaculture treatment facilities.

Englande and Tridech(6,7) also found that, almost universally, aquatic plants exhibit initial rapid uptake of trace contaminants, like cadmium, which gradually

Table 2.1

RELATIVE UPTAKE EFFICIENCY OF WASTE CONTAMINANTS
BY AQUATIC PLANTS IN BATCH STUDY: 28-DAY DETENTION TIME(6,7)

Plant	Pollutant (% removal)										
	As	B	Cd	Hg	Se	Phenol	PCB	Tot-N	PO_4	BOD_5	TOC
Bulrush	82.14	14.62	98.85	92.75	94.89	100	100	99.62	89.55	87.70	59.52
Rush	54.22	12.64	91.44	79.13	61.80	100	100	99.97	65.41	92.66	70.15
Arrowhead	10.53	16.47	78.41	74.17	29.77	100	100	62.73	7.51	85.28	61.15
Water Hyacinth	12.50	12.46	68.60	70.16	8.19	100	100	41.70	13.30	21.76	18.04
Duckweed	10.26	16.95	68.00	68.86	10.98	100	100	50.55	17.67	14.44	18.8-47.6
Waterbonnet	0.62	10.67	24.85	47.42	6.11	100	57.14	58.53	20.59	-5.00	1.55
Coontail	15.82	17.63	91.11	70.01	28.89	100	100	92.28	-4.64	23.33	18.94
Elodea	20.75	17.52	85.71	79.19	18.28	100	100	94.23	8.19	49.28	54.05
Alligator Weed	11.80	14.62	76.30	75.18	10.52	100	100	96.50	38.06	82.57	57.60
Algae	---	10.91	46.17	62.20	0.00	100	87.50	72.23	-0.71	30.36	6.15
Control (no plants)	4.35	1.49	22.75	60.39	0.00	100	66.67	59.99	-0.91	-7.55	1.75

approaches an equilibrium level after approximately 10 to 30 days. The rate of uptake varies with plant species and contaminant concentration. This finding indicates the necessity of harvesting mature plants from the system in order to remove the trace contaminants continuously. Two mathematical models were proposed by Englande and Tridech to describe absorption or tissue uptake kinetics for various vascular aquatic plants.

Based on the results of the batch screening study, a continuous flow study with and without effluent recirculation was conducted for water hyacinths and bulrushes. Selection of water hyacinth and bulrushes for continuous flow studies was also based on practical considerations such as productivity of the plants, ease of harvesting, and high removal capacity for most trace contaminants. The experimental results for continuous flow without recirculation and with 1:1 recirculation are summarized in Table 2.2.(6,7) It can be seen that overall removal of all pollutants was better with aquatic plants than in the control system without plants. Removal of fecal coliforms by the control system and planted systems is believed to be primarily due to natural die-off resulting from the hostile environment in the bench scale treatment systems. Improved removal by effluent recirculation may be the result of increased probability of contact between the liquid and plants, increased renewal rate of reactive interfaces, and stabilization of overall treatment process, which are the basic governing design principles for the design of conventional trickling filters and biological towers with plastic media for bacterial growth (a fixed film treatment process).(6,7)

2.2 Existing Wastewater Aquaculture Facilities

Although interest in wastewater aquaculture technology has increased, in part due to construction grant funding incentives through EPA's Innovative/Alternative (I/A) Technology Program, application of wastewater aquaculture technology remains primarily an academic interest. Full-scale, permanent application of wastewater aquaculture technology is still rather rare. This Section summarizes the treatment objective, size, and level of performance of reported, existing aquaculture treatment systems.

2.2.1 Existing Aquaculture Treatment Systems Using Aquatic Plants

Table 2.2

REMOVAL OF TRACE AND CONVENTIONAL POLLUTANTS BY WATER HYACINTH AND BULRUSH (6,7)

System	BOD_5	TOC	As	B	Cd	Hg	Se	Phenol	PCB	TN	PO_4	TSS	VSS	F. Coli	Eff. pH	Det. Time (days)
Water Hyacinth without Recirculation	95	80	41	36	85	92	60	97	98	85	65	99	99	99.5	7.0-7.6	15
Water Hyacinth with 1:1 Recirculation	95	70	52	11	61	96	51	89	100	84	19	98	97	99.9	6.9-7.7	7.5
Bulrush without Recirculation	76	66	56	36	91	93	85	96	95	75	52	94	91	95.3	7.2-7.7	15
Bulrush with 1:1 Recirculation	95	68	63	37	90	98	91	86	100	88	17	99	98	99.9	7.2-7.8	7.5
Control (no plants) without Recirculation	70	27	7	0	81	82	45	72	26	73	22	81	73	94.5	8.3-9.3	15
Control (no plants) with 1:1 Recirculation	81	48	23	*	39	93	21	77	100	76	*	89	86	98.3	7.9-8.3	7.5

*Increased

Aquaculture treatment systems using aquatic plants rather than fish or aquatic invertebrates seem to be predominant in the application of wastewater aquaculture technology. Many aquatic plant species including water hyacinths, reeds, bulrushes, cattails, duckweed, alligatorweed, primrose, kelps and others are potential candidates for aquaculture treatment systems.

Existing operative aquaculture treatment systems which use aquatic plants are listed in Table 2.3. As indicated, water hyacinth has been the most commonly used plant for wastewater aquaculture facilities. Reeds/bulrushes rank second, Duckweeds are the third most popular aquatic plant species in aquaculture treatment systems. Existing aquaculture treatment system using aquatic plants tend to be relatively small-flow facilities since:

- Most systems are experimental or pilot plant size and thus tend to be small-flow facilities; and
- Land requirements for aquaculture treatment systems tend to favor its application in rural areas where large flows are not generally found.

Most of the existing documented aquaculture treatment facilities are of a various research nature and have been sponsored by U.S. federal governmental agencies and research institutions including the National Aeronautic and Space Administration (NASA), the U.S. Environmental Protection Agency (EPA), the National Science Foundation, Woods Hole Oceanographic Institution, Tennessee Valley Authority, Tulane University, University of California at Davis, Humboldt State University, Florida State University, Michigan State University, and Walt Disney World. Few projects have been privately funded. A great majority of the systems treat domestic or municipal wastewater with emphasis on renovation of secondary effluent or lagoon effluent. The lack of research funds or the termination of a research project was found to be the primary cause for many systems becoming non-operative. Only a few systems have become non-operative because of system problems such as plant die-offs or mosquito infestations. The identifiable non-operative plant-based aquaculture treatment systems are listed in Table 2.4. In general, technical reports on existing systems are limited to those of an experimental nature.

2.2.2 Water Hyacinth Aquaculture Treatment Systems

Table 2.3

EXISTING PLANT WASTEWATER AQUATIC PROCESSING UNITS (APU)

Location	Species Used	Treatment Objective	Flow (MGD)	Description
N.S.T.L., Bay St. Louis, MS	hyacinth, duckweed	photographic wastewater	0.024	hyacinth lagoon (zig zag)
"	"	raw wastewater	N/A	hyacinth & duckweed lagoon
"	"	"	"	"
"	"	"	"	"
"	"	"	"	"
"	"	"	"	"
Shreveport, LA	hyacinth	screened raw wastewater	0.014	hyacinth lagoon (spray irrigated when cold)
Paragould, AS	duckweed	primary effluent	2.2	lagoon
N. Biloxi, MS	duckweed	aerated lagoon effluent	0.013	0.08 Ha aerated lagoon duckweed; duckweed pond
Gregory, TX	hyacinth	secondary effluents & stormwater	0.14	ditch with hyacinth; lake with hyacinth
Austin, TX	hyacinth	waste activated sludge	1.6	3 sludge ponds in series; hyacinth pond
Rio Hondo, TX	hyacinth	stabilization pond effluent	0.12	stabilization pond; 3 hyacinth ponds in series
				Imhoff tank; stabilization pond;

Location	Species Used	Treatment Objective	Flow (MGD)	Description
Edcouch, TX	hyacinth	pond effluent	0.14	ponds
Coral Springs, FL	hyacinth	secondary effluent	0.1	hyacinth ponds in in series
Walt Disney World, FL	hyacinth	primary effluent	0.063	3 hyacinth lagoons in series
Plant City, FL	hyacinth	secondary effluent	4.0	hyacinth pond
Chapel Hill Independent School District, TX	hyacinth	raw wastewater	0.02	hyacinth pond
Hanover, NH	cattails vegetables	primary effluent	0.003	nutrient film technique
N.S.T.L. Bay St. Louis, MS	anaerobic filter/reed	septic tank effluent	N/A	anaerobic filter/ reed system
Lake Helen, FL	hyacinth	primary	0.007	4 lagoons in serie methane generation

ABANDONED PLANT APU'S

Location	Plant(s) Used	Treatment Objective	Flow (MGD)	Description	Reason for Abandonment
San Marcos, TX	Hyacinth	Aerated wastewater	0.028	Wind power aeration basin; recirculation hyacinth pond	Research terminated
Rio, TX (San Juan)	Hyacinth	Stabilization pond effluent	1.0	Aerated pond; stabilization pond; 2 hyacinth ponds in parallel	Funding stopped with deletion of sewer commission
Rio, TX (Alamo)	Hyacinth	Stabilization pond effluent	0.4	Imhoff tank; trickling filter; aerated basin in series; 2 stabilization ponds; 2 hyacinth ponds in parallel	Funding stopped with deletion of sewer commission
San Benito, TX	Hyacinth	Stabilization pond effluent	1.75	3 stabilization ponds in series; hyacinth pond	Mosquito problem from overloading
Gainesville, FL U. of FL	Hyacinth	Secondary effluent	0.7	Secondary treatment; 3 cell polishing pond (last pond hyacinths)	Research terminated
Lakeland, FL	Hyacinth	Secondary effluent	0.15	3 hyacinth lagoons in series	Research terminated
Gaseme, FL	Hyacinth	Secondary effluent	1.0	Hyacinth lagoon	Plants froze, not replaced
Lucedale, MS	Hyacinth	Raw wastewater	0.25	Hyacinth lagoon	Research terminated
Orange Grove, MS	Hyacinth	Aerated lagoon effluent	1.0	series; 3 hyacinth lagoons in parallel	Hyacinths grew too fast, removed
Baytown, TX (Exxon)	Hyacinth	Stabilization pond effluent	N/A	N/A	Research terminated
St. Helena, CA	Hyacinth	N/A	N/A	N/A	Mosquito infestation
Forestville, CA	Hyacinth	N/A	N/A	N/A	Mosquito infestation
Occidental, CA	Hyacinth	N/A	N/A	N/A	Mosquito infestation
Piney Woods Baptist Encampment, TX	Hyacinth	N/A	N/A	N/A	Plants did not survive
Texarkana, TX	Hyacinth	N/A	N/A	N/A	Plants did not survive
Lewisville, AK	Hyacinth	N/A	N/A	N/A	Plants did not survive

Water hyacinths (Eichhornia crassipes) are large floating aquatic plants that were introduced into the southern United States from tropical regions. Research has indicated that water hyacinth production is on the order of 1,000 to 10,000 wet-pounds/day-acre (1,120 to 11,200 kg/ha-day), ranking it as one of the most productive plants on earth. Water hyacinth plants have been found to grow at a rate of 10 percent of their surface area per day(8,9,10) and thrive in raw or partially treated sewage. In fact, hyacinth growth in treated sewage is reported to be double the growth rate in natural waters.(11) Water hyacinths are relatively resistant to insects and disease, are unaffected by pH variations from 4 to 8, but are sensitive to high salinity and above-water plant tissues die back rapidly as temperatures approach freezing. Due to temperature effects, water hyacinth has a very limited geographic range without auxiliary heating or cover of hyacinth ponds. The water hyacinth contains between 0.7 percent and 3.7 percent nitrogen and between 0.1 percent and 0.9 percent phosphorus on a dry weight basis. This is equivalent to a nitrogen removal potential of approximately 770 kg/ha-yr and a phosphorus removal potential of approximately 180 kg/ha-yr based on 95 percent water content(12).

The high growth rate, resistance to insects, disease and presence of an extensive root system where microorganisms can attach, are favorable characteristics of the water hyacinth and have led to its popularity in wastewater aquaculture technology(13).

Basically, wastewater aquaculture treatment by water hyacinth is currently accomplished by passing raw or pre-treated wastewater through a basin, or series of basins, covered with water hyacinths. Through the complex mechanisms discussed previously, the plants remove BOD, suspended solids, nutrients, metals, and possibly other contaminants. Harvested hyacinths from these systems have potential use as fertilizer/soil conditioners, animal feeds, and as a source of methane through anaerobic digestion, after appropriate handling and processing steps.

Most of the existing hyacinth treatment systems are in the development stage. The ability of water hyacinths to remove BOD, SS, nutrients, metals, and certain organic compounds from wastewaters has been documented in laboratory scale studies. A number of full scale experimental and demonstration systems have also been implemented. However, most of the work with water hyacinth treatment systems has sought to monitor and document overall treatment effects rather than to describe and quantify removal mechanisms and specific removal rates at various stage of growth, under various environmental stresses. The continued study of removal mechanisms and rates is necessary if optimization system design and operation criteria is ever to be achieved.

The ability of water hyacinths to remove BOD and suspended solids enables hyacinth-based technology to be applied to treatment of raw municipal and domestic wastewaters, primary effluents and stabilization pond effluents. The ability to remove heavy metals and organic compounds implies that water hyacinth systems may also be used in treating certain industrial wastewaters. Certain types of industrial wasteflows have been experimented with in hyacinth-based systems. The results of these experiments are discussed in Chapter 3.

Most frequently, water hyacinth systems have been used as an advanced treatment process to remove nutrients from conventional secondary treatment plant effluents or to retard algal growth in conventional lagoon treatment systems. Reducing algal growth in conventional treatment lagoons by planting and growing water hyacinths has been documented.(14) While these studies used effluent suspended solids as an indicator of algal growth, it is believed that additional evidence supporting the supression of algal growth by water hyacinth coverage could be provided by measuring chlorophyl-a concentration.

Climate is a major constraint in implementing a water hyacinth treatment system. Active growth of water hyacinth begins when the water temperature rises above 10°C (50°F) and flourishes when the water temperature is approximately 21°C (70°F).(13) This water temperature range can only be maintained cost-effectively in regions of the United States where above freezing temperatures occur on a year-round basis. Water hyacinths die rapidly when the water temperature approaches the freezing point. Greenhouse construction would be necessary in those states where winter freezes occur if water hyacinth systems were to be used on a year-round basis.

Water hyacinth treatment systems characteristically require large acreage. It has been estimated that 2 to 15 acres of land is required to treat a 1 MGD flow. Therefore, water hyacinth treatment systems may not be practical in areas where land is not economically available.

As indicated previously, continuous or periodic harvesting of water hyacinths, especially the selective harvest of those plants showing symptoms of aging, is desirable to maintain treatment efficiency. Due to the large size of the plants, harvest is more readily accomplished for hyacinth than for other aquatic species such as duckweed or algae. Several harvesting techniques have been tried. These include on-shore drag lines fitted with clam-shell buckets, retrievable nets, and specially designed mechanical harvesters.

The water hyacinth is normally 92 to 95 percent water.(14) If the harvested plants are to be used as fertilizers/soil conditioners or in animal feeds, extensive dewatering/drying is necessary. In order to release inter-cellular water, the water hyacinths need to be chopped or shredded. Further dewatering can be achieved through mechanical pressing. However, the most cost-effective method of drying hyacinths is through solar energy on drying beds. Greenhouse construction may be necessary in some parts of the country to facilitate this drying process. Composting dewatered water hyacinths is a potential means of stabilizing water hyacinths for later use as a soil conditioner. Use of water hyacinths for fertilizers/soil conditioners or animal feeds may be limited when heavy metal and other toxic substance concentrations are accumulated in the water hyacinth tissue. Anaerobic digestion of water hyacinths to generate methane gas would be a possible use for these plants. However, maintenance of proper conditions in the digesters may not always be possible in many parts of the country without auxiliary heating of the digesters in cold weather periods. In addition, anaerobic sludge from the digesters needs to be disposed of in an environmentally sound manner.

2.2.3 Duckweed Aquaculture Treatment Systems

Duckweeds, (Lemnaceae), are among the smallest floating plants known. The Family Lemnaceae consists of the genera; Wolffiella, Wolffia, Spirodela, and Lemna. In most instances, mixed cultures of duckweed species are found.

It has been estimated that the productivity of mixed duckweeds growing in wastewater lagoons is approximately 37 dry kkg per hectare per year (16 dry tons/acre-yr).(15) The water content of fresh duckweed is approximately 95 percent. Therefore, this productivity is equivalent to 350 wet kkg/ha-year (or 310 wet tons/acre-yr). Duckweed contains from 1.2 percent to 7.2 percent nitrogen and from 0.2 to 2.8 percent phosphorus on dry weight basis. This equates to a nitrogen removal potential of approximately 550 to 750 kg/ha-year (490 to 670 pounds/acre-yr) and a phosphorus removal potential of 140 to 260 kg/ha-yr (or 125 to 230 pounds/acre-yr).(15) This higher nitrogen content found in duckweeds gives it a higher feed value compared to most aquatic plants.

Duckweed species, in general, are more tolerant of cold weather than water hyacinths. It has been reported that common duckweed vegetates at temperatures as low as 1°C(15,16) and will survive light freezes. Duckweed growth has been found to continue at a slower rate during the winter months, and thus it may be applied to aquaculture treatment systems over a much wider geographical area than water hyacinths. However, in areas where severe and extended winter periods occur, greenhouse construction would be necessary to assure process reliability.

The rapid growth, ease in harvest by screening or straining, longer growing season and relatively favorable feed value of duckweed render it a prominent candidate for wastewater aquaculture treatment systems.

Current wastewater aquaculture treatment systems using duckweed are similar to water hyacinth treatment systems. Raw wastewater or pretreated wastewater is introduced to a basin or multiple basins in series which are covered with duckweed. Through previously discussed mechanisms, duckweeds facilitate the removal of BOD, suspended solids, organic compounds and heavy metals from the water column. Because the root zone is much shallower than that of the water hyacinth, removal of suspended BOD and other suspended solids via root zone filtration by duckweed is much less than by water hyacinth.

Most of the existing duckweed treatment systems are in the development or experimental stage. It has been demonstrated that duckweed can effectively remove BOD, SS, nutrients, and trace contaminants from wastewaters in laboratory and pilot scale studies. At the time of this study there were two demonstration systems in operation. One system at Biloxi, Mississippi polished the effluent from an aerated lagoon treating raw sewage.(17) The other treated dairy farm wastes in a study at Louisiana State University, Baton Rouge, Louisiana. The level of performance of the Biloxi, Mississippi system plus the results of a three-month winter test conducted at National Space Technology Laboratories (NSTL), Bay St. Louis, Mississippi, are given in Table 2.5.

A small laboratory scale study conducted by the University of Florida(16) to determine the nutrient removal potential of duckweed, demonstrated that nitrate nitrogen removal efficiencies were 0, 10, 20, 28 and 29 percent for detention times of 2, 4, 6, 8 and 10 days, respectively. The nitrate nitrogen removal essentially reached equilibrium level at a detention time of 8 to 10 days. Removal efficiencies of phosphorus attributable to duckweed uptake were approximately 6, 9, 23, 34 and 48 percent for detention times of 2, 4, 6, 8 and 10 days, respectively.(16) Apparently, the equilibrium phosphorus removal rate was not attained in this experiment, because the detention time was not long enough and mechanisms discussed previously would affect this equilibrium removal rate. This laboratory scale test also demonstrated the rapid growth rate of duckweed. Lemna was found to double in frond number, and thus area of coverage, every 4 days under favorable environmental conditions.(16) Thus, if an acre (0.4 ha) of effluent was one-fourth covered by Lemna at Day 0, at Day 8, it would be completely covered. Other interesting preliminary findings of this study were:(16)

- Wolffia columbiana, while having a high digestability (or dietary) value, was found to be difficult to harvest.
- Salvinia rotundifolia was found to contribute large amounts of detrital material to the benthos and was found to have a very low digestability (or dietary) value.

Similar to water hyacinths, duckweed treatment systems require relatively large land areas. Duckweed treatment systems probably can be cost-effective in areas where land is economically available. Continuous or periodic harvest of duckweed, especially mature individuals is the key to maintaining maximum system productivity and treatment performance. Harvesting duckweed is

Table 2.5

PERFORMANCE OF DUCKWEED AQUATIC TREATMENT SYSTEMS

Location	Type of Wastewater Applied	Influent (mg/l)		Effluent (mg/l)		Percent Removal	
		BOD	TSS	BOD	TSS	BOD	TSS
North Biloxi, MI (Wolverton, 1979)	Effluent from Aerated Lagoon Domestic Sewage	16-37(35)	61-397(155)	8-28(15)	8-22(14)	15-69(48)	80-98(88)
National Space Technology Lab Bay St. Louis, MS* (Wolverton, 1979)	Aerated Lagoon Effluent	69-90(82)	88-132(111)	2-7(3.7)	8-14(10)	92-98(96)	89-93(91)

* 3-Month experiment in winter

relatively more difficult than harvesting water hyacinths due to the smaller size of duckweed. Skimmers, strainers, screen buckets, screens, and similar devices (manual or automated systems) have been used for harvesting duckweed.

The handling and processing of harvested duckweed may include dewatering, drying, composting, anaerobic digestion and/or other processing steps as necessary. Potential end uses of harvested duckweed include animal feed supplements, and soil conditioners.

2.2.4 Reed/Bulrush Aquaculture Treatment Systems

Reeds or bulrushes are emergent rooted aquatic plants. There are several experimental systems using reeds and/or bulrushes. Among the varieties of reeds and bulrush, Phragmites communis (a reed), Scirpus lacustris (a bulrush), and Scirpus validus (a soft stem bulrush) have been tested successfully for wastewater treatment.(2,18,19) In the aquaculture treatment field, aquaculture treatment systems using emergent aquatic plants including reeds, bulrushes, cattails, etc. are considered forms of artificial wetland treatment systems, and are discussed further in Section 2.3.6.

2.2.5 Existing Combined Aquaculture Treatment Systems

A combined aquaculture treatment system, or polyculture treatment system, is generally defined as one in which wastewater treatment is accomplished by several different trophic levels of cultured aquatic organisms. In typical polyculture treatment systems, carbonaceous compounds are broken down biologically by microorganisms and nutrients are first converted to single-cell organisms or lower forms of plants that serve as food for organisms of higher trophic levels in the same aquatic processing unit (APU) or in subsequent APU's.(20)

There are fewer existing combined aquaculture treatment systems than systems using aquatic plants only. Those facilities using combined APU's are most often associated with other plant APU's or wetlands APUs due to the fact that in general, a polishing APU using plants is necessary to further renovate effluent in order to remove animal wastes. A number of the combined processes that have been reported are illustrated in Figure 2.1. In addition, available information regarding the combined aquaculture treatment or polyculture concept results from research and demonstration projects that have been terminated. Table 2.6 lists some of the published polyculture research projects.

When floating aquatic plants (e.g. duckweed, water hyacinth, etc.) are used in an aquaculture treatment system, it is possible to grow selected fish or aquatic invertebrates in the same pond. In general, duckweed or water hyacinth ponds are shallow (liquid depth of 3 to 4 feet) and are subjected to winter freezing. This may adversely affect the growth of aquatic animals in the system and thus result in poor system performance in winter. For a combined system using bulrushes and reeds grown hydroponically, the animal APU requires a separate pond. Algae ponds in a combined aquaculture treatment system, in general, should precede and be separated from any aquatic animal ponds to eliminate low dissolved oxygen problems in the aquatic animal ponds. Combined aquaculture treatment systems are not usually used to treat raw sewage directly. They are used most often to renovate secondarily treated effluent. In general, combined aquaculture treatment systems are not as easily controlled as aquaculture treatment systems using aquatic plants only.(20).

The Quail Creek Wastewater Treatment System, Oklahoma City, Oklahoma used six ponds in series, the first two of which were artificially aerated. Tilapia, fathead minnows, and channel catfish were grown in the third pond, channel catfish in fourth pond, and golden shiners and minows in the fifth and sixth ponds.(21) Another system at the Village of Dorchester, Wisconsin(24) used an aerated sewage treatment lagoon for rearing muskellunge fingerlings. Conventional lagoon treatment and aquaculture treatment were accomplished in the same lagoon. In addition, a 6-pond system utilizing silver carp (Hypothalmichthyes molitrix) and big head carp (Aristichthyes robilis) for the treatment of primary effluent was used in experiments by Henderson(25)(26).

Researchers at Michigan State University(22) used four ponds in series to test the performance of the combined aquaculture treatment concept on primary and secondary effluents. The first pond was intended primarily as an algae pond

Figure 2.1

POSSIBLE LIQUID PROCESS TRAINS FOR COMBINED AQUACULTURE TREATMENT SYSTEMS(21-24)

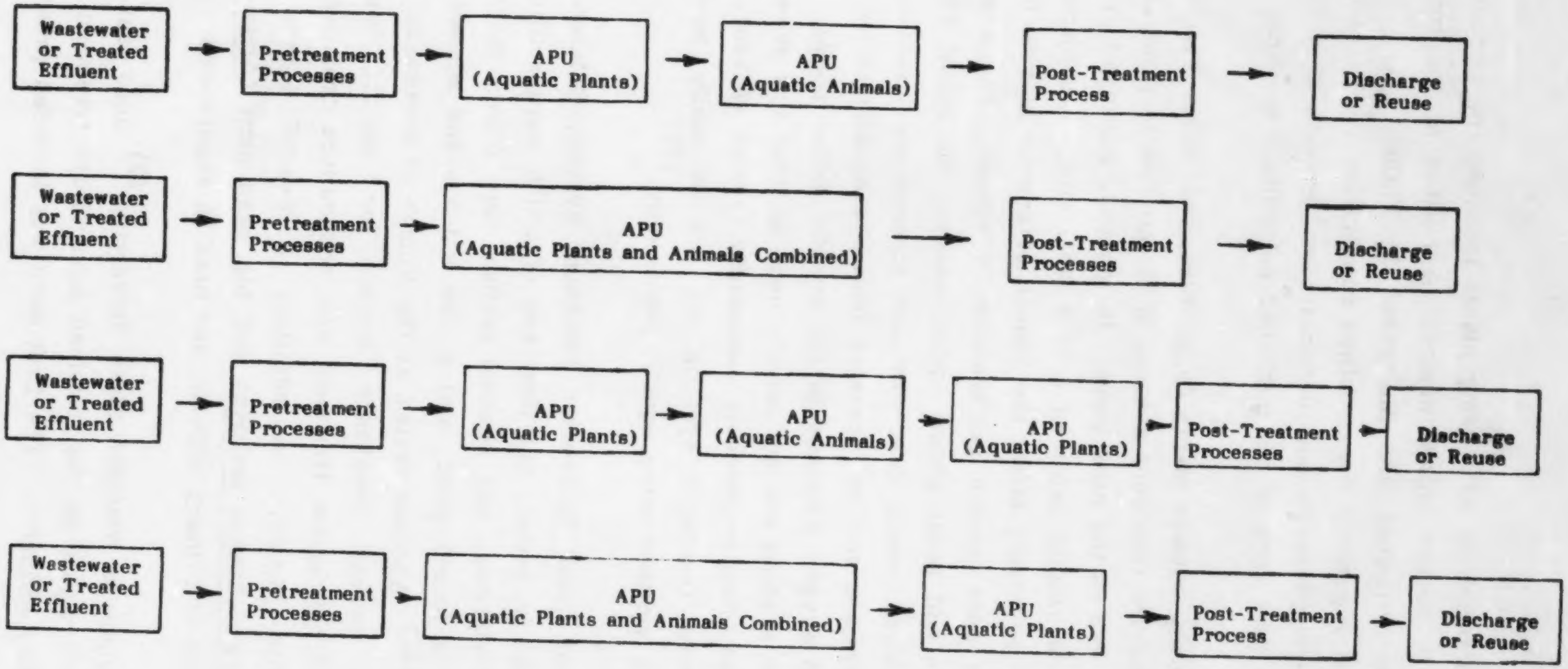

Wastewater or Treated Effluent
Pretreatment Processes
APU (Aquatic Plants)
APU (Aquatic Animals)
Post-Treatment Process
Discharge or Reuse
Wastewater or Treated Effluent
Pretreatment Processes
APU (Aquatic Plants and Animals Combined)
Post-Treatment Processes
Discharge or Reuse
Wastewater or Treated Effluent
Pretreatment Processes
APU (Aquatic Plants)
APU (Aquatic Animals)
APU (Aquatic Plants)
Post-Treatment Processes
Discharge or Reuse
Wastewater or Treated Effluent
Pretreatment Processes
APU (Aquatic Plants and Animals Combined)
APU (Aquatic Plants)
Post-Treatment Process
Discharge or Reuse

Table 2.6

Polyculture (Combined) APU Research Projects

Location	Plant(s), Animal(s) Used	Treatment Objective	Flow (MGD)	Description	Reason for Abandonment
Quail Creek, OK	Catfish, tilapia golden shiner minnows	2° effluent	1.0	6 lagoons in series; fish in last 4	Research terminated
Enid, OK	fish, mussels water primrose	Refinery wastewater toxicity	0.014	6 pools in series; algae first 3 and plants in last 3	Research terminated
Oak Ridge Lab, TN	Tilapia	2° effluent	0.023	2 oxidation ponds in series containing fish	Research terminated
Austin, TX	shrimp, snails fathead minnows goldfish, carp tilapia	Filtered secondary effluent	0.03	Hyacinths duckweed, snails, scud 1st unit; zooplankton in 2nd unit, shrimp and fish in final 2 units	Research terminated
Woods Hole, MA	Algae shellfish	2° effluent	0.008	Cultured algae; mixed with seawater; fed to shellfish (mariculture)	Research terminated
Harbour Branch, FL	Algae, carp, shrimp	2° effluent	0.002	Cultured algae fed to fish and shrimp	Research terminated
Solano Beach, CA	Hyacinth duckweed invertebrates	2° effluent	0.001	Solar aquacell process	Research terminated
Hercules, CA	Hyacinth invertebrates	1° effluent	0.35	Solar aquacell process	Operational problems
Michigan State University, MI	Algae, Elodea Largemouth bass	1°,2° effluent	0.5 MGD	4 ponds in series; algae in 1st, elodea in last 3, with bass in final	Being phased out
Benton Services Center, AS	Silver, Bighead Carp	2° effluent	0.4 MGD	6 lagoons in series; 1st, 2nd with algae & plankton culture, final 4 with fish.	Experimental, pilot scale.

supporting periphytic algae species. After a brief bloom of planktonic algae, the other three ponds were dominated by the macrophyte Elodea canadensis. Largemouth bass were grown in the last pond. It was noted that the growth of largemouth bass was very rapid from average body length of 4.4 cm (1.7 inches) to 24.9 cm (9.8 inches) in approximately 12 months.

Dinges(27) studied, on a pilot scale basis, a five-step biological treatment system consisting of a filter and a four-cell culture unit. The system was designed to treat the effluent from a stabilization lagoon after filtration. The first cell, approximately one-half of the culture unit, contained water hyacinths, duckweeds, snails, scuds, and various insects. The second cell was designed to culture zooplankton and duckweed, with the duckweed intended to suppress algal growth. Shrimp and fish were grown in the third and fourth cells, respectively.

The treatment performances of the aforementioned systems, summarized in Table 2.7, indicate removals of BOD, TSS, and total nitrogen greater than 67 percent, 55 percent, and 60 percent depending on influent quality. Removal of total phosphorus greater than 74 percent is possible in the earlier stage of the systems.(21) However, long-term removal of total phosphorus is rather low, approximately 17 percent, as demonstrated by the Benton, Arkansas project after several years of experiments.(25,26) This may be attributable to the saturation of phosphorus in the pond sediments and loading or breakthrough of soluble phosphorus.

2.2.6 Natural Wetlands Aquaculture Treatment Systems

Natural wetlands, both marine and freshwater, have inadvertently served as natural waste treatment systems for centuries. U.S. EPA Regions IV and V are currently inventorying the use of natural wetlands areas for wastewater disposal in those regions, in efforts to quantify and qualify environmental impacts. The managed use of wetlands for wastewater treatment is a relatively recent development dating back to the early 1960's(29) Table 2.8 lists a number of published facilities where wetlands are either utilized as disposal sites (in many cases having discharged for several decades) or managed as tertiary treatment sites. The list is by no means complete, as the EPA's region V alone has

Table 2.7

LEVEL OF PERFORMANCE OF COMBINED AQUACULTURE TREATMENT SYSTEMS

Project	Average Removal Percent						
	Influent	BOD	TSS	Total N	Total P	Fec. Coli	Period of Experiment
Quail Creek, Oklahoma City, OK	Secondary Effluent	75	83	61	74	98.6	4 mo.
Village of Dorchester, Wausan, WI	Raw Sewage	97.5	96.4	--	--	--	2 yr.
Michigan State University East Langing, MI	Primary or Secondary Effluent	--	--	98	98	--	existing
5-Step Polyculture System, Williamson Creek, Austin, TX	Filtered Secondary Effluent	77	80	81	--	99	--
Benton Service Center, AS	Primary Effluent	67	55	60	17	--	2 yr.

References (20-26)

Table 2.8

EXISTING NATURAL WETLANDS TREATMENT SITES

Location	Objective	Size	Type of Wetlands	Remarks
Mt. View Sanitary District, CA	treatment of 2° effluent	.7 MGD	volunteer marsh-forest	existing
Beaver Bay, MN	tertiary treatment of 2° effluent	.04 MGD	peatland	N/A
Wildwood, FL	disposal of 2° effluent	N/A	natural cyprus dome wetlands	N/A
Walt Disney World, FL	disposal of 2° effluent	2.0 MGD	pine and cypress wetlands	existing
Drummond, WI	pipeline irrigation of 2° effluent	.01 MGD	bog, adjacent to hardwoods & sphagnum wetlands	N/A
Houghton Lake, MI	tertiary treatment of 2° effluent	.01 MGD	marsh peatland wetlands	existing
Vermontville, MI	tertiary treatment of 2° effluent	.5 MGD	volunteer cattail marsh	existing
Concord MS	discharge of 2° effluent	.61 MGD	deep marsh-Nat'l Wildlife Refuge	18 Mos. Study
Brillion Marsh, WS	tertiary treatment of 2° effluent	.02 MGD	natural freshwater marsh	
Gainesville, FL	tertiary treatment of 2° effluent	.0015 MGD	cypress dome swamps	existing

identified 96 sites using wetlands areas for disposal. There are undoubtedly numerous unpublished natural wetlands disposal sites throughout the United States.

In recent years, marshes, swamps, bogs, peatlands and other wetlands have been successfully utilized as managed natural "nutrient sinks" for polishing partially treated effluents.(30) Natural wetlands areas receiving managed discharges of secondary effluent for tertiary treatment purposes are numerous. Houghton Lake, Michigan is one such facility where research beginning in 1972, led to the 1978 construction of a gated-pipe irrigation system to disperse secondary municipal effluent over 600 acres of natural wetlands for the purpose of tertiary treatment.(31) Williams and Sutherland(32) identify five other wetlands areas in Michigan alone where municipal wastewater/wetlands effects are being investigated. These include Kinross, Lake Odessa, Vermontville, Paw Paw and Leoni Township.

Cypress dome wetlands have demonstrated the potential for providing tertiary treatment of secondary effluent while remaining environmentally sound. Cypress dome wetlands are characteristically saucer-shaped swamps containing cypress trees, the tallest of which are located in the center of the dome. The bottom of the ponds are coated with organic sediments and clay, which promote slow filtering of the wastewaters through soil.(33) Trees rooted in the soil with attached bacteria, and pond surface duckweeds facilitate treatment of the wastewater as it passes through the system to underlying groundwaters.

Secondary effluent from a mobile home park located near Gainesville, Florida was purposely applied to a cypress dome wetland location for research purposes. Ninety-eight percent of the total nitrogen and 97 percent of the total phosphorus was removed before entering the underlying groundwater.(34) Other monitored parameters in the groundwater of two test domes and control units were below Federal Drinking Water Standards.

The discharge of wastewater effluents to cypress wetlands has occurred in other locations in Florida as well. A cypress strand wetlands in Jasper, Florida has also received discharges of secondary effluent for several years, and is being evaluated for tertiary treatment efficiency.(35)

Phosphorus removal mechanisms in wetlands aquaculture treatment systems are significantly affected by the type of soil present in the wetlands and the sorption, ion exchange and precipitation reactions taking place between the soil and wastewater.(36) The most significant nitrogen removal mechanism appears to be bacterial nitrification/denitrification processes.(36)

The removal of nitrogen and phosphorus is also affected by vegetative uptake, and the frequency of harvesting. Harvesting is not commonly practiced for natural wetland systems.

BOD removal information and loading rates have been summarized by Stowell, et al(33) for peatland and marsh systems. It was observed that effluent BOD was relatively constant, better than conventional tertiary treatment systems, and relatively independent of influent BOD for natural wetland systems. In addition, BOD removal rates (BOD removed per unit area and unit time) were reported to be a linear function of BOD loading rates as long as detention times generally greater than 15 days were provided, and BOD loading rates were less than 80 kg/ha-day (approximately 70 pounds/day).(36)

Secondary effluents may provide a unique opportunity to recover damaged or stressed wetlands while properly disposing of the treated effluents at the same time. Wildlife habitat enhancement of this kind has been successfully demonstrated in Mountain View Sanitary District, California.(37) The 23-acre reclaimed wetlands area studied included open water areas, open water areas with artificial substrates for aquatic invertebrate populations (called ecofloats), mud flats and cultivated areas of floating and emergent vegetation, levees and adjacent wet lands with terrestrial grasses, shrubs and trees. The plant species occurring indigenously in the wetlands numbered 72, and 90 species of birds were identified living in or visiting the wastewater created wetlands.(37)

In addition to the resultant flourishing wildlife habitat, wastewater effluent quality improves as it passes through the wetlands environment. Data indicate fluctuating levels of nutrients, BOD and suspended solids, all which are affected and changed by the life cycles taking place in the ecosystem. Demgen(37) stresses that BOD and suspended solids contained in the wetlands effluent is in a highly useable form; comprised mainly of algae cells and other organisms that are primary food sources in the aquatic environment. The recycling effect afforded by the wetlands environment alters the unuseable nutrients, BOD and suspended solids of human waste origin to plant biomass and other natural forms.

Wetland treatment systems are relatively land intensive (perhaps not as land intensive as slow-rate irrigation land treatment) requiring land in the order of 8 to 10 acres per million gallons per day.(30) Therefore, wetland systems may prove impractical for large treatment facilities due to the extensive land requirements.

2.2.7 Artificial Wetlands Aquaculture Treatment Systems

The construction of artificial wetlands systems has been proposed as an alternative to conventional treatment processes and offers another option in areas where natural wetlands do not exist or are restricted from use by environmental protection laws. Constructing a wetlands area where one did not exist previously can be beneficial in several aspects. Constructed wetlands offer more potential for operation and design controls than natural wetlands. Examples of better control through design can be observed in the provision of liners throughout the system to prevent infiltration/percolation to groundwater, or providing treatment cells in a marsh, where flow can be terminated in one cell to facilitate harvesting, while treatment continues in other cells. Artificial wetlands generally consist of shallow ponds, channels, basins, or trenches planted with different types of aquatic plant species including bulrushes, reeds, cattails, coontails, or alligator weeds. Several existing systems as listed in Table 2.9 have been successfully demonstrated to treat primary and secondary effluents.

Small(39), at Brookhaven National Laboratories experimented with constructed marsh-pond-meadow systems used to treat raw wastewaters (aerated, screened) to secondary levels. Two independent experimental systems have been reported (39,40), one a constructed meadow-marsh-pond, the other a marsh-pond system treating flows of 12,000 to 40,000 gallons/day. The aquatic processing units (APUs) of the meadow-marsh-pond system consisted of grassed meadow overland-flow APU followed by a cattail marsh APU flowing to a pond APU

Table 2.9

EXISTING ARTIFICIAL WETLANDS APU's

Location	Species Used	Treatment Objective	Flow (MGD)	Description
Santee, CA	reeds and bulrush	treatment of secondary effluent	0.1	secondary effluent applied to reed and bulrush wetland
Petaluma, CA	cattail and bulrush	treatment of secondary effluent	0.04	secondary effluent applied to cattail and bulrush wetland
Easton, MD	reed	treatment of lagoon effluent	0.016	secondary effluent applied to reed bed
Neshaminy Falls, PA	cattails meadow	treatment of raw wastewater	0.03	screening, aerated pond, constructed marsh; oxidation pond, constructed meadow in series
Orange County, NY	variety of indigenous species	treatment of primary effluent	0.03	2 independent systems marsh/pond/meadow in series meadow/pond marsh in series

stocked with fish and invertebrates. The system was arranged in series with recycling options provided among the APUs. The marsh-pond system was similar, lacking only the meadow. Both systems operated effectively, resulting in the recommendation of deleting the meadow. Additional research-oriented artificial wetlands projects that have been terminated are listed in Table 2.10.

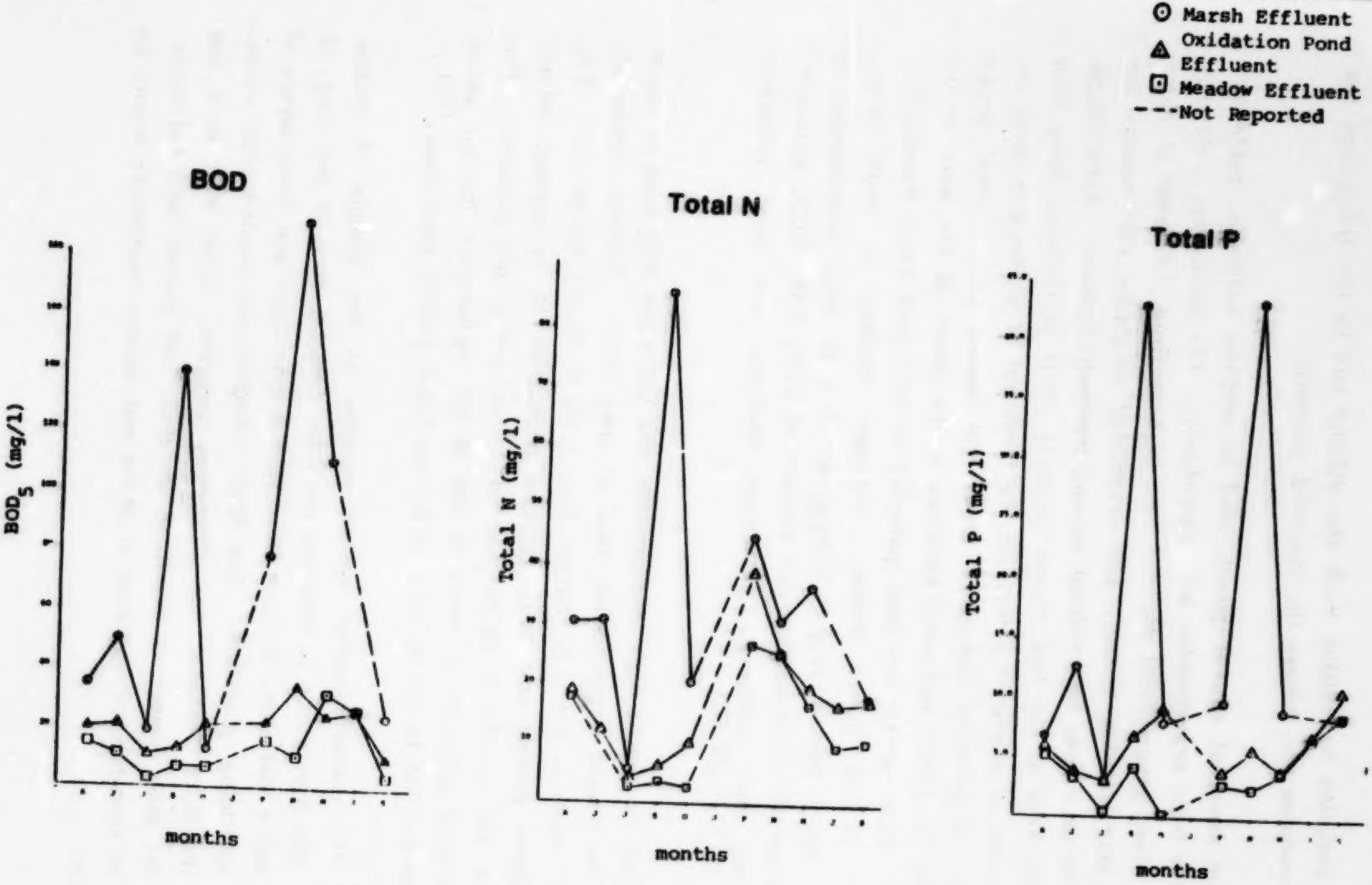
Small's work in Brookhaven was used as a guideline in developing a marsh-pond-meadow system for the Village of Neshaminy Falls, Pennsylvania(40). Neshaminy Falls is a mobile home retirement community with a domestic wastewater flow of 20,000 gallons/day. Following a membrane-lined aerated basin there are: a 4-cell cattail marsh APU; an intermittantly aerated pond APU; and a 4-cell overland-flow meadow APU, in series. The marsh, pond and meadow APUs are lined with bentonite clay overlain with gravel and sand. Maintenance on the system includes cutting the meadow monthly, distributing the flow among the four cells of the marsh and the meadow, and periodically activating the aeration unit in the pond in summer to prevent algae blooms, and in winter to prevent icing over. The groundskeeper for the mobile home park is responsible for these tasks.

The marsh-pond-meadow system at Neshaminy Falls has demonstrated consistently effective reduction of BOD and SS to secondary levels and during the growing season, treatment to tertiary levels resulting from the uptake of nutrients by the marsh plants and meadow grasses. Odor and insect problems have been minimal, and the system has been observed to provide an environment for several species of birds, fishes and other animals. Figure 2.2 illustrates the effectiveness in removal of several wastewater parameters over a period of a year and a half.

From the Figure 2.2, it is obvious that a significant problem in controlling the seasonal variation of nitrogen and phosphorus in the final effluent exists. This operational problem can be explained by the die back of the wetland vegetation during the fall, and the consequent decomposition and release of nutrients during the early part of the year. In spite of this problem, adequate treatment still takes place resulting from the biological activity of the microorganisms still active in the root system of the wetland plants. It may be possible to reduce

Table 2.10
ABANDONED ARTIFICIAL WETLANDS APU'S

Location	Plant(s) Used	Treatment Objective	Flow (MGD)	Description	Reason for Abandonment
Brookhaven, NY	Cattails duckweed Canary grass	Mixture of screened raw wastewater and septage	.01 to .04	2 independent systems: meadow/marsh/pond marsh/pond	Research terminated
M. Niguel, CA	Reeds and bulrushes	Raw sewage and 2° effluent	.035 to .025	Reeds in filter trench; bulrush in polishing trench	Research terminated
Greenport, NY	Reeds and bulrushes	Raw sewage and 2° effluent	N/A	"	Research terminated
Port Jefferson, NY	Reeds and bulrushes	Milk bottling wastewater	N/A	"	Research terminated
Port Charlotte, FL	Reeds and bulrushes	2° effluent	.004	"	Research terminated
Westport, CT	Reeds and bulrushes	2° effluent	N/A	"	Research terminated
Sumter, SC	Reeds and bulrushes	2° effluent	N/A	"	Research terminated



Removal Performance for Artificial Wetlands
Aquaculture System, Neshaminy Falls, PA
(April, 1980 - September, 1981)

Figure 2.2

the seasonal variation by cutting back the wetland late in the fall before the plants can decompose and release the absorbed nutrients.

Among various emergent aquatic plants used in aritifical wetlands, reeds and bulrushes have been experimented with extensively. The hardiness, resistance to diseases, wider geographical regions, ease of harvesting, tolerance to wider pH ranges, long growing season, and overwinter capability are reasons for selecting reeds or rushes for artificial wetland treatment systems. Kathe Seidel and her co-workers at the Max Planck Institute (MPI) in Germany have been studying the use of emergent plants for the treatment of wastewater since the early 1950's. A patented system of reeds and rushes (MPI system) grown hydroponically in gravel and sand trenches is the result of her work at the Institute.(2) This system has been patented by Biological Water Purification, Inc. (BWPI) in the United States. Managed plantings of reeds (e.g., *Phyragmites* spp.) rushes (e.g., *Scirpus* spp.) have been demonstrated to reliably provide pH neutralization and removal of BOD, TSS, COD, nutrients, heavy metals, fecal coliforms, pathogenic bacteria, and some refractory organics.(2,18,19,41,42,43)

Reeds have an inherently high transpiration rate but a low unit mass of leaves moderates the overall transpiration rate of reed beds. Biomass production reported for reeds in the U.S. ranged from 6,540 to 39,900 kg/ha-year. The combined above ground and below ground production in hydroponic culture ranges from 230 to 74,010 kg/ha-year in 1- to 3-year old cultures. The nitrogen removal potential of reeds is 330 to 800 kg/ha-year for the above ground mass and 350 to 830 kg/ha-year for the below ground plant mass.(43)

A typical MPI reeds/bulrushes system consists of two groups of shallow trenches. The first group of trenches are filter trenches each 75 feet long, 12 feet wide, and 4 feet deep, and are filled with a sand layer and three layers of gravel of ascending gradation. The filter trenches are planted with reeds. Following the filter trenches are elimination trenches, filled with sand and gravel in the same manner as the filter trenches, but planted with bulrushes. Both sets of trenches are operated in series and receive wastewater evenly by gravity flow.

Basically, the filter trenches remove a majority of suspended solids through physical filtration and biological breakdown. The latter is predominently achieved by microorganisms attached to plant roots and residing in the gravel or sand medium. It is postulated that active growth of the root system within the sand or gravel medium prevents clogging of the sand or gravel layers. In addition, it is hypothesized that some enzymatic excretions by plant roots are effective in killing some enteric and pathogenic bacteria present in the wastewater and thus disinfecting the wastewater.

Typical levels of performance by an MPI system are summarized in Table 2.11 for secondary and tertiary treatment.

A hybrid wastewater treatment system consisting of a settling tank in series with an anaerobic reed (Phragmites communis) treatment cell treating lagoon effluent was evaluated by Wolverton(43) and compared with a similar system without the reeds (control system) in a greenhouse with minimum and maximum temperatures averaging 19°C and 35°C, respectively. The control system exhibited 62 percent removal of BOD_5 and the reed system was able to achieve 91 percent removal of BOD_5 when hydraulic detention was maintained at 6 hours. When the hydraulic detention time was increased to 24 hours, the control system showed 87 percent and 64 percent removals of BOD_5 and TSS respectively, while the reed system indicated 96 percent and 96 percent removal of BOD_5 and TSS respectively. The reed system was capable of reducing ammonia nitrogen from 10.8 mg/l (influent) to 0.8 mg/l (effluent), total Kjeldahl nitrogen (TKN) from 16.4 mg/l to 3.5 mg/l, and total phosphorus from 4.7 to 2.1 mg/l after 24 hours of detention.

Lakshman(41) used cattail (Typha latifolia) and bulrush (Scirpus validus) for treatment of raw sewage in an indoor summer-lot environment in a static batch manner. Gravel substrate was used to support the plants. These experiments demonstrated significant removal of TKN and total phosphorus by both cattail and bulrush systems. These static experiments indicated that there are equilibrium levels of removal of nutrients by both cattail and bulrush systems. Harvesting will promote growth of new plant mass and facilitate further removal of nutrients.

Table 2.11

LEVEL OF PERFORMANCE OF REEDS/BULRUSHES
TREATMENT SYSTEM MPI SYSTEM AT LAGUNA NIGUEL, CALIFORNIA(42)

Secondary Treatment	% Removal					
	BOD_5	TSS	COD	NH_4-N	Org-N	TP
September, 1978	87	91	80	52	73	15
October, 1978	89	90	81	46	67	7
November, 1978	87	90	75	30	54	3
December, 1978	86	92	78	25	73	9
January, 1979	82	86	79	26	41	-14
February, 1979	87	91	78	42	-27	0
March, 1979	85	91	78	24	50	10
April, 1979	81	90	76	14	22	11
May, 1979	84	86	78	13	57	16
June, 1979	83	91	77	14	40	-12
July, 1979	78	92	73	---	---	2
AVERAGE	84.5	90	77.5	28.6	45.0	4.3
Tertiary Treatment						
AVERAGE	54	53	39	50	---	13

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CHAPTER 3

AMENABILITY OF WASTEWATERS TO AQUACULTURAL APPLICATIONS

3.0 INTRODUCTION

Prerequisite to an assessment of why aquaculture is not more widely used as a wastewater treatment method is an identification of the types of wastewaters potentially amenable to aquaculture treatment. External influences (i.e. climate) affecting treatment feasibility for a particular wastewater source are not a factor in assessing amenability. In this case, amenability is synonymous with treatability.

In general, wastewaters treatable with biological processes are candidates for aquaculture treatment. As indicated in Chapter 2, typical domestic wastewaters and municipal wastewaters have been shown to be amenable to aquaculture treatment processes. Additionally, certain industrial and agricultural wastewaters have been shown to be amenable, and others appear to have a potential for aquaculture treatability.

3.1 Amenability Assessment Methodology

The methodology used in performing the following amenability assessment involved obtaining a categorization of industrial wastewater sources. The scope of this survey intended that broad classifications of wastewaters be inventoried for amenability. It is recognized that the composition of wastewaters can vary among sources within the same industrial classification and can vary among individual municipal sources. While actual treatability studies would be necessary before applying an aquaculture treatment process to a particular wastewater source, certain generalizations regarding amenability to treatment are possible.

As a source of information regarding the typical composition of wastewaters characteristic of each industrial classification, reference was made to the U.S. EPA Guidelines for State and Local Pretreatment Programs.(1) Amenability was assumed based on a general set of criteria which included the following:

- Previous demonstration of amenability in a bench, pilot or full scale wastewater aquaculture treatment facility;
- History of amenability to conventional biological treatment processes or recommended for biological pretreatment methods in the aforementioned guidelines;
- Minimal pretreatment prior to biological treatment;
- Non-excessive chemical/physical pretreatment to remove toxic or corrosive components and/or non-excessive addition of essential nutrients for biological sustenance.

Major industrial categories of wastewaters are listed in Table 3.1 together with the significant pollutants present and treatment history. Those categories which do not treat wastewaters with conventional biological processes, but rather with other physical/chemical treatment methods include:

- Electroplating, Metal Finishing
- Inorganic Chemical Industry
- Soap and Detergents
- Fertilizer
- Iron and Steel
- Nonferrous Metals
- Phosphate
- Steam Electric Power*
- Ferro Alloys
- Asbestos
- Rubber
- Water Supply
- Paint and Ink Formulating
- Steam Supply and Noncontact Cooling*

* Candidate for thermal effluent aquaculture (Chapter 4).

These industrial wastewater categories were eliminated from further amenability assessment under the assumption that other chemical or physical methods are more suitable than biological treatment. However, some of these wastewater categories may become amenable through pretreatment, which might include removal of heavy metals, temperature reduction, oil and grease removal, pH adjustment, etc. In addition, those wastewaters which specifically lack

Table 3.1

SIGNIFICANT POLLUTANTS OF MAJOR INDUSTRIAL CATEGORIES

Industry	CFR* No.	BOD	TSS	TDS	COD	pH	P	N	Oil & Grease	Heavy Metals	History** Biological Treatment
Dairy	405	X	X		X	X	X	X	X		yes
Grain Mills	406	X	X	X	X	X	X	X*			yes
Canned and Preserved Fruits & Vegetables	407	X	X			X	X	X*			yes
Canned and Preserved Seafood	408	X	X		X				X		yes
Sugar	409	X	X	X				X			yes
Textiles	410	X	X			X			X	X	yes
Cement	411		X		X		X			X	no
Feedlots	412	X	X		X	X	X	X			yes
Electroplating Metal Finishing	413		X	X		X	X			X	no
Organic Chemical Industry	414	X	X	X	X			X		X	yes
Inorganic Chemical Industry	415		X	X		X				X	no
Plastics & Synthetics	416	x	x		x				x	x	yes, pretreatment

Table 3.1 (con't)

Industry	CFR* No.	BOD	TSS	TDS	COD	pH	P	N	Oil & Grease	Heavy Metals	History** Biological Treatment
Soap and Detergent	417	X	X		X				X		no
Fertilizer	418		X			X	X	X		X	no
Petroleum	419	X	X	X	X	X	X	X	X	X	yes, pretreatment
Iron and Steel	420	X	X					X	X	X	no
Nonferrous Metals	421		X	X	X				X	X	no
Phosphate	422		X			X	X			X	no
Steam Electric Power	423	X	X		X	X	X	X	X	X	no
Ferro Alloys	424		X	X		X		X		X	no
Leather	425	X	X		X	X		X	X		yes, pretreatment
Glass	426	X	X	X	X	X	X	X	X		yes, pretreatment
Asbestos	427	X	X	X	X	X	X	X	X		no
Rubber	428	X	X	X	X				X	X	no
Timber	429	X	X		X	X	X		X		yes
Pulp, Paper, Paperboard	430	X	X						X	X	yes, pretreatment
Builders Paper and Roofing Felt	431	X	X								yes
Meat Products	432	X	X	X	X	X	X	X	X		yes

Table 3.1 (Cont'd)

Industry	CFR* No.	BOD	TSS	TDS	COD	pH	P	N	Oil & Grease	Heavy Metals	History** Biological Treatment
Water Supply	437	X	X	X	X	X				X	no
Food and Beverage	438	X	X						X	X	yes, pretreatment
Misc. Chemicals	439	X	X	X	X	X		X		X	yes
Auto and Other Laundries	444	X	X	X	X	X			X	X	yes/no
Paint and Ink Formulating	446 & 447	X	X		X	X		X	X	X	no
Steam Supply & Noncontact Cooling	449		X	X	X	X	X	X	X	X	no

* Code of Federal Regulations Title 40: parts 425

** U.S.EPA 1977 Federal Guidelines - State & Local Pretreatment Programs, 1977.

nutrients, may be amenable to aquaculture treatment through discharge to a Publically Owned Treatment Works (POTW), where mixing and blending with other wastewaters may amend the nutrient deficiency. Nutrient addition could also be accomplished by combining certain industrial and agricultural wastewaters. In the case where a POTW contains an APU or is a system of APU's, an inventory of the industries and their wastewater characteristics would be necessary to prevent the discharge of toxic or corrosive wastes to the aquaculture system that may result in process upset.

An example of a POTW which contains an APU exists in Plant City, Florida(2). The 8 MGD activated sludge treatment plant is followed by a water hyacinth lagoon APU designed for effluent polishing. The following industries contribute roughly 60 percent of the present flow through the facility:

- Pork Processing Plant
- Aluminum Extrusion Plant
- Candied Fruit Company
- Instant Tea Company
- Frozen Food Company
- Fruit Processor
- Ice Cream Plant
- Laundromat
- Battery Reclamation Plant.

Wastewater derived solely from the aluminum extrusion process would be an unlikely candidate for wastewater aquaculture, lacking nutrients and containing significant concentrations of chemical wastes. Through pretreatment and discharge to the POTW, blending, dilution and nutrient addition take place, which allows conventional and aquaculture treatment to follow without interference to the biological system. In fact, the aluminum discharged to the POTW may be beneficial to the system by facilitating the removal of phosphorus through precipitation. Those industries remaining from Table 3.1 were assessed for amenability to aquaculture treatment according to the aforementioned criteria. Table 3.2 lists the industries assessed, the pollutant characteristics present, a nutrient assessment and brief discussion by major categories.

Several of the industrial categories listed in Table 3.2 contain wastewaters that have been tested experimentally in wastewater aquaculture systems. These include meats and poultry, petroleum refining, pulp mills, photographic and pharmaceutical industries.

Table 3.2
Wastewater Amenability for Aquaculture Uses

Wastewater Category	BOD (mg/l)	Suspended Solids (mg/l)	Nutrient Availability	Amenability for Aquaculture Uses
Dairy				
Milk, Milk Products	40-10,000	40-2,000	P:9-210 (mg/l) N:1-115 (mg/l)	Suitable after BOD removal
Grains				
Corn (wet)	225-7600	81-2458	P:present N:0-10 (mg/l)	Suitable after BOD removal and temperature reduction, may be N deficient
Corn (dry)	600-2748	1038-3485	P:0-10 (mg/l) N:0-10 (mg/l)	Suitable after BOD reduction, may be N deficient
Wheat	nil	nil	N:0-10 (mg/l)	Unsuitable
Bulgur	238-521	294-414	P:5.6 (mg/l) N:0-10 (mg/l)	Suitable, however high temp and N-deficiency may constrain
Rice (parboiled)	1280-1305	33-77	P:30-65 (mg/l) N:7.0 (mg/l)	Suitable after BOD removal, high temp
Ready-To-Eat Cereals	420-2500	80-1573	P:Present N:5-30 (mg/l)	Suitable, however some processes generate high temperature wastewaters.
Starch & Gluten	6200-14,633	4,176-14,824	P:103 (mg/l) N:350-400 (mg/l)	Suitable after BOD and SS reduction
Meats and Poultry				
Beef Cattle (runoff)	1700	35,000	P:90 (mg/l) N:200 (mg/l)	Very good potential for aquaculture treatment of wastewaters from concentrated feedlot operations. High solids and BOD may be inhibiting to some systems. Several wastewaters tried in experimental aquaculture. See abstract.
Dairy Cattle (milk wastes)	4000	2,400	P:60 (mg/l) N:450 (mg/l)	
Swine (manure)	2500-20,000	9,000	P:400 (mg/l) N:3000 (mg/l)	
Swine (runoff)	100	260	P:5 (mg/l) N:20 (mg/l)	
Sheep & Lambs (manure)	7000	35,000	P:2000 (mg/l) N:800 (mg/l)	

ABSTRACT

Small dairy and grain milling industries occur throughout the United States. However, the larger, more concentrated industrial activities occur in the midwestern grain producing states. The characteristically high BOD loads present in wastewaters of these industries may constrain their use in aquaculture. High temperature wastewaters resulting from several grain milling processes can be beneficial to aquaculture systems during cold weather periods by extending the treatment process, however it can also be detrimental by reducing the amount of dissolved oxygen in the water. Temperature and BOD reductions and in some cases, nutrient addition, can improve the amenability of wastewaters in the dairy and grain milling industries.

ABSTRACT

Highly concentrated animal feedlots common in western and midwestern states produce runoff wastewaters extremely high in BOD and suspended solids. Wastewaters from both the feddlots industry and meat packing industries are amenable to aquaculture treatment, in most cases only requiring BOD reduction and grease removal. Experimental aquaculture has been performed using swine and poultry wastes (3), (4) and cattle wastes (5).

Table 3.2 (con't)

Wastewater Category	BOD (mg/1)	Suspended Solids (mg/1)	Nutrient Availability	Amenability for Aquaculture Use
Sheep & Lambs (runoff)	3000-12,000	8,000	P:80-750 (mg/1) N:1000 (mg/1)	
Ducks (wet lot)	500	4,000	P:70 (mg/1) N:50 (mg/1)	
Meat Products				
Slaughterhouse (simple)	500-1400	70-1500	P:9.4 (mg/1) TKN:128 (mg/1)	
Slaughterhouse (complex)	500-1400	70-150	TKN:114 (mg/1)	
Low-Processing Packing House	500-1400	70-1500	P:17 (mg/1) TKN:68 (mg/1)	
High Processing Packing House	500-1400	70-1500	P:30 (mg/1) TKN:105 (mg/)	
Small Processor	500-1400	70-1500	P:70 (mg/1) TKN:200 (mg/1)	Meat products processing wastewaters may require some BOD reduction and grease removal. General amenability good.
	500-1400	70-1500	P:8 (mg/1) TK[illegible]	
Sausage & Luncheon Meats	500-1400	70-1500	P:20 TKN:25	
Ham Processor	500-1400	70-1500	P:28 TKN:20	
Meat Canner	500-1400	70-1500	P:80 TKN:40	
Canned and Preserved				
Fruits and Vegetables	500-5000	19-24,300	can be nitrogen deficient	Highly variable concentrations of BOD, SS from subcategory to subcategory. Excessive BOD and suspended solids may require reduction prior to aquaculture use.

ABSTRACT

Seafood processing industries are most commonly located in coastal areas, while fruits and vegetables processing occurs throughout the United States. Both industrial categories may require reduction in BOD and Suspended Solids prior to aquaculture treatment, however most wastewaters are amenable. Seafood product processing wastewaters may require oil and grease removal as well.

Table 3.2 (con't)

Wastewater Category	BOD (mg/l)	Suspended Solids (mg/l)	Nutrient Availability	Amenability for Aquaculture Use
Canned and Preserved Seafood				
Crab (Blue, Alaskan, Dungeness)	270-4400	60-620	good	Suitable providing excessive oil, grease and BOD reduction provided
Shrimp (Alaskan, West Coast Southern)	720-2000	800-300	good	"
Clams, Oysters, Scallops	200-10,000	27-6,000	good	"
Finfishes, Fish Meal	100-6000	100-5000	good	"
Miscellaneous Food and Beverages				
Vegetable Oils	340-60,000	1,000-57,000	adequate	Suitable if oil and grease pretreatment is available, BOD reduction may be necessary
Beverages (alcoholic and nonalcoholic)	200-5,800	50-5,700	adequate	Suitable
Bakery & Confectionary	400-28,000	100-5,000	adequate	Suitable with BOD reduction, oil and grease removal
Pet Foods	200-12,000	200-9,000	adequate	Suitable
Specialty Products	1,000-6,000	130-1,900	adequate	Suitable with BOD reduction
Sugar Processing				
Crystalline Cane	13-263	2-397	TKN:0.60-1.66 NO_3-N	Suitable if adequate nutrients available
Liquid Cane	72-487	59-796	TKN:0.51	"
Beet	857	3,216	---	"

ABSTRACT

Miscellaneous food and beverage industries occur throughout the U.S. while major sugar producing states include Louisiana, Texas and Hawaii. Wastewaters from these industries are generally very amenable to aquaculture treatment provided BOD reduction can be accomplished when necessary and adequate nutrients are available to support the aquatic systems.

Table 3.2 (con't)

Wastewater Category	BOD (mg/l)	Suspended Solids (mg/l)	Nutrient Availability	Amenability for Aquaculture Uses
Textiles				Conditional Amenability
Wool (scouring and finishing)	100-8,000	25-10,000	N/A	Nutrient addition may be necessary as well as oil and grease removal)
Woven & Knit (finishing)	30-1,800	1-800	N/A	Suitable, suspended solids and color reduction may be necessary nutrient addition & pH adjustment
Carpet	40-500	50-120	N/A	Suitable, if nutrient addition practised-color
Stock & Yarn	150-600	10-50	N/A	Sulfide and chrome present-may also be nutrient deficient
Leather Tanning	1,100-4,000	1,400-4,000	TKN:100-600 (mg/l)	High pH, excessive alkalinity and presence of chormium may constrain aquaculture uses
Timber Products	3-16,000	4-40,000	P:0-6500 (mg/l) N:N/A	Most wastes biodegradable, however, some processing techniques result in organic chemical wastes. pH adjustment and oil and grease removal may be necessary.
Pulp and Paper	60-5,000	40-5,000	present	Heavy metals may be present
Builders Paper and Roofing Felt	130-3,000	75-10,000	N/A	
Pharmaceutical	100-11,000	10-7,000	NP present in some	Generally biodegradable. BOD reduction necessary in some wastewaters Experimental Aquaculture.(10)
Photographic	300	25	Kjel-N-100 (mg/l)	Presence of Fe, Cy, Au and B may constrain use in aquatic system if in high concentrations. Experimental Aquaculture.(9)(10)
Petroleum Refining	10-800	10-300	NH_3-N-.05-250(mg/l)	Different refining process yield PO_4-P-.1-10 (mg/l)highly variable wastewaters which contain organic and inorganic chemicals. Experimental Aquaculture.(7)

ABSTRACT

The further noted categories of industrial wastewaters have been treated biologically ,however some wastewaters may contain pollutants harmful to aquatic systems. Pretreatment prior to application in an aquaculture system may include BOD reduction, suspended solids reduction, temperature reduction and nutrient addition to particular wastewater flows.

Table 3.2 (con't)

Wastewater Category	BOD (mg/l)	Suspended Solids (mg/l)	Nutrient Availability	Amenability for Aquaculture Uses
Organic Chemicals	100-500	10-4,000	NH_3-N 1-1000(mg/l)	Metals can be harmful to aquatic systems. High TDS may constrain use in aquatic system.
Auto and Other Laundries	650-1,300	95-5,000	N/A	Heavy metals present in some wastewater categories (Auto & Industrial). Nutrient addition may be necessary as well as pH adjustment, oil and grease and removal.

The category of meats and poultry includes all industries involved in high and low intensity animal feedlot operations for beef and dairy cattle, swine, sheep, lambs and poultry. Several feedlot wastewater flows have been proven amenable to aquaculture treatment in bench and pilot scale investigations. For example, poultry and swine wastes have been applied to Tilapia aurea culture ponds(3), swine wastes have been used in the culture of grass, silver and bighead carp(4), and beef cattle manure has been used to culture duckweed(5). The recycling of feedlot wastes on-site in a wastewater aquaculture facility provides an opportunity for the livestock owner to reduce feed costs by harvesting the aquatic vegetation or organisms and processing them for use in animal feeds. Culley and Epps(6) found that wastewater cultured duckweed compared favorably in terms of nutritional content with conventional animal feeds.

Exxon Company petroleum refinery wastewaters in Baytown, Texas were treated successfully with water hyacinth APU's, which effectively treated the wastewaters even during periods of winter kill.(7) The water hyacinths harvested from the APU exhibited an abundance of accumulated metals such as zinc, chromium, molybdenum and nickel. The uptake of metals, phenol and other contaminants by water hyacinths or other APU macrophytes used to treat wastewaters in the petroleum industry will undoubtedly constrain the use of the harvested biomass by-products.

Bench scale wastewater aquaculture has been evaluated for pulp mill effluents at Weyerhauser Corp. in Washington using the crustacean Moina macrocopa for total suspended solids reduction.(8) The organism, which appears seasonally, was found to reduce the total suspended solids, and when harvested and assessed for marketability, exhibited the potential for use as a conventional aquaculture or tropical fish food.

Photographic and chemical wastewaters at the National Space Technology Laboratories (NSTL) in Bay St. Louis, Mississippi, have been treated successfully by water hyacinth APU's.(9) Water hyacinths in this system demonstrated the capability of accumulating heavy metals.

Pharmaceutical wastes have been used experimentally in wastewater aquaculture as a food source for Tilapia aurea in the form of spent beer and spent beer plus solids.(10) As a food source, the spent beer trials indicated that the organic materials present in the spent beer were suitable sources of food for the rearing of Tilapia aurea. While this portion of pharmaceutical wastewaters are amenable to aquaculture, wastewaters generated in the formulation of other pharmaceutical products may contain heavy metals or other contaminants in concentrations not compatible with aquatic biological treatment systems.

Wastewater aquaculture treatment in several other industrial categories may provide a unique opportunity for the recycling of wastes through the processing of wastewater aquaculture by-products, and use of those by-products in animal feeds and feed supplements. For example, particular grain milling industry subcategories produce wastewaters that appear amenable to aquaculture treatment. If those wastewaters were applied to a plant or fish-based APU, the harvested biomass from the APU may be useable as an animal feed or supplement. It has been suggested that water hyacinths and other aquatic macrophytes can be dried and ensiled to produce suitable animal feeds.(11) In addition, fish harvested from an APU may be processed for use as a protein supplement in animal feeds(12) or used as fertilizer on adjacent grain producing croplands.(13)

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CHAPTER 4

GEOGRAPHICAL VARIABLES WHICH AFFECT UTILIZATION OF AQUACULTURE TECHNOLOGIES

4.0 GENERAL

In addition to the characteristics of wastewater flows which prescribe their amenability to aquaculture treatment, a series of environmental variables also influence aquatic wastewater treatment systems. These variables are generally climatological and hydrogeological in nature. Table 4.1 summarizes the pertinent variables of each group. In order to address fully the impact of these variables on parameters such as geographic location, design, operation and maintenance, each variable is discussed relative to wastewater aquaculture in this chapter.

The environmental requirements of aquatic treatment species have been intensively investigated and reported in a series of four publications for the California State Water Resources Control Board.(1) Because many of the environmental requirements discussed are a function of climatological and hydrogeological conditions, these publications are excellent references for specific species information.

4.1 Climatological Variables

4.1.1 Solar Insolation

Solar energy, the driving force of photosynthesis, is essential to the aquatic animals, plants, algae and microorganisms which inhabit a wastewater aquaculture treatment system. In aquatic environments, the amount of solar energy available affects the rate of photosynthesis, thus the oxygen supply, pH

Table 4.1

CLIMATOLOGICAL AND HYDROGEOLOGICAL VARIABLES AFFECTING AQUACULTURE

Climatological Variables	Hydrogeological Variables
Solar Insolation	Instream Flow
Temperature	Surface Runoff
Precipitation	Flood Potential
Evaporation/Transpiration	Groundwater Availability
Wind	Natural Wetlands Proximity
Heating and Cooling Degree Days	

and carbonate concentration, and the rate of evaporation and evapotranspiration.

Solar insolation values are important in determining the quantity of activation energy available in an aquatic treatment system to accomplish photosynthesis. Photosynthetic reactions are primarily responsible for the removal and uptake of macronutrients (nitrogen and phosphorus) by aquatic plants and animals. Thus solar energy drives an essential part of the wastewater treatment process. In northern latitudes, the influx of solar energy may not be seasonally sufficient to maintain adequate photosynthesis rates.

In summary, the quantity of solar energy entering an aquatic system is a stimulant essential to the plants and animals inhabiting the system and it is often a limiting factor. Table 4.2 illustrates this concept by demonstrating the probable yield of algal mass from a typical municipal wastewater treated by an optimally designed and operated algae aquaculture treatment system based on naturally available sunshine. It is apparent that an aquaculture treatment system in lower latitudes can be more effective than a similarly designed system at higher latitudes.

4.1.2 Temperature

Ambient temperature is affected by the solar insolation availability in a given area and varies with latitude. Mean temperature, in combination with other climatological parameters dictates the evaporation and evapotranspiration potential at a given locality. Ambient temperature, like solar energy undergoes diurnal and seasonal variation. Heating and cooling degree days are an effective expression of the annual variation in ambient temperature. In a broader sense, heating/cooling degree days for a given locality can be used effectively to estimate the length of growing season for a given aquatic species. The life associated with the aquatic environment in any location has its species composition and activity regulated by water temperature. Since essentially all of the organisms in wastewater aquaculture facilities are "cold blooded" or poikilotherms, the temperature of the water regulates their metabolism and ability to survive and reproduce effectively.(3) Temperature, is a catalyst, or

Table 4.2
Range of Probable Yield of Algae From a
Properly Designed Algae Aquaculture System (lb/ac-day)

LATITUDE Deg. N or S		Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	Max	54.0	63.8	65.0	63.8	59.8	56.6	57.1	60.5	64.5	63.6	61.4	60.7
	Min	50.4	52.6	49.4	45.1	43.7	24.7	32.9	40.1	49.7	48.7	48.5	46.8
10	Max	53.5	58.6	63.4	65.0	64.8	62.9	63.6	63.9	63.9	59.5	54.7	54.0
	Min	43.0	44.2	46.3	43.9	46.1	31.0	37.9	42.2	47.0	43.4	42.2	38.9
20	Max	43.9	51.1	59.0	65.0	68.2	68.2	67.7	65.3	60.5	53.8	45.6	43.7
	Min	32.2	33.6	40.3	40.8	46.7	35.5	41.3	42.3	42.2	36.0	33.1	28.8
30	Max	32.6	42.2	52.3	62.6	69.6	71.0	69.4	65.0	55.4	46.1	35.5	30.2
	Min	18.2	23.0	32.2	36.2	44.2	39.1	42.7	39.0	35.3	27.1	21.6	16.1
40	Max	19.2	31.2	43.4	43.4	68.6	71.5	69.1	61.9	48.7	36.5	22.8	15.8
	Min	7.2	12.7	77.8	30.0	38.7	41.5	41.3	35.3	26.9	17.3	10.1	5.8
50	Max	6.7	16.8	33.8	50.4	65.0	71.3	67.2	67.2	39.8	24.0	9.2	6.2
	Min	2.4	4.6	13.9	23.3	24.6	42.2	37.2	30.0	17.5	9.6	3.6	1.7
60	Max	1.7	7.7	25.7	42.2	59.8	70.6	64.3	49.2	30.2	10.2	2.4	1.2
	Min	0.5	1.0	7.9	19.0	31.7	41.8	34.6	24.0	9.1	6.2	0.7	0.2

Note: Computed values derived from McGaughey(2) depressant, an activator, a restrictor, a stimulator, a controller, and a killer, and is therefore one of most influencial variables to wastewater aquaculture.

Temperature determines the growth conditions of aquatic species in an aquaculture treatment system, and also dictates aeration requirements. Temperature also affects the self-purification phenomenon in water bodies and therefore the aesthetic and sanitary qualities that exist. Indicator enteric bacteria, and presumably enteric pathogens, are likewise affected by temperature. It has been shown that both total and fecal coliform bacteria die away more rapidly in the environment with increasing temperatures.(4) This effect has great implication in the design of an aquaculture treatment system, since it offers a potential mechanism to control by-product contamination by microorganisms.

Temperature changes in water bodies can alter species variety and dominance in the aquatic community. The aspect of temperature as a variable influences to a great degree the selection of aquatic species for an aquaculture treatment system and the requirements for pretreatment such as cooling or heating of wastewaters. Several methods have been successfully applied to remedy off-season temperature problems inherently associated with certain aquaculture treatment processes. These methods include:

- Storage of wastewater during cold weather periods and application to the aquaculture treatment system during periods when the temperature permits.
- Provision of a greenhouse to maintain system temperature within a desirable range for aquatic species growth and maintenance.
- Supplemental with thermal effluents from power plants or industrial boilers.

There are currently no known wastewater aquaculture facilities which use thermal waste heat effluents to maintain active populations of aquatic species during cold weather periods to continue the treatment process. There are however, several "clean" water aquaculture facilities throughout the United States which utilize thermal power plant effluents to extend the growing season of cultured aquatic species. A number of aquaculture facilities that practice thermal aquaculture at power plant sites are listed in Table 4.3. The experience gained through aquaculture research in the power generating

Table 4.3

THERMAL AQUACULTURE FACILITIES

Location	Species	Comment
Public Service Electric and Gas Co., Mercer Generating Station, NJ	tilapia, trout	Demonstration with thermal
Tennessee Valley Authority, Brown's Ferry Nuclear Plant, Athens, AL	tilapia	Experimental thermal
Astro-Marine Industries, Hawaii	golden tilapia	Experimental with thermal
So. Carolina Public Service Authority, Santee Cooper, South Carolina	tilapia, ells, catfish	Full scale with tilapia experimental with catfish
Pennsylvania Power & Light, Pennsylvania	channel catfish	Current expanding pilot facility
Southern California, Edison Ventura Los Angeles,	lobster, abalone	2 coastal power plants, one demonstration, the other bench scale
Tennessee Valley Authority, Gallatin Power Plant, Tennessee	trout, catfish	N/A
Basin Electric Power Coop. Leland Olds Station, North Dakota	trout	Commercial Scale

industry may be of value in wastewater aquaculture systems located in northern climates.

4.1.3 Precipitation

Precipitation takes many forms including rain, snow, hail, glaze (freezing rain) and ice pellets. Excessive rain may result in some undesirable effects on aquaculture treatment systems. These effects may include:

- Dilution of wastewater to the extent that is no longer compatible with certain aquaculture treatment systems.
- Short-circuiting of the wastewater resulting in inadequate treatment and resuspension of settled solids.
- Erosion and/or siltation of certain aquaculture treatment systems due to excessive runoff resulting from precipitation.
- Flooding or undesirable inundation of certain aquaculture treatment systems.

The annual variation in quantity and type of precipitation in a given area should be considered in the design of an aquaculture treatment system. Some aquatic species are vulnerable to one form of precipitation or another. For example, natural aquaculture systems using floating plant species such as duckweed or water hyacinth are vulnerable to washout by excessive rain and runoff. In addition, the low pH of rainfall in certain northern areas of the United States can be detrimental to aquatic plants and animals in an aquaculture system. Precipitation in the form of snow, hail, glaze or ice pellets in general is harmful to aquaculture treatment systems and should be considered as part of planning and design efforts.

4.1.4 Evaporation and Evapotranspiration

Evaporation is influenced by physical parameters of the ambient environment such as air temperature, water temperature, humidity, barometric pressure, windspeed, solar insolation. Local evaporation potential influences the predominant aquatic species in a given locality. Use of an aquatic species from coastal zones in an arid region may present adaptation problems in terms of evaporation potential in addition to other climatological variables. Excessive evaporation rates may result in dessication of plants and effect their growth. In addition, evaporative losses may result in increased concentrations of salts and/or other pollutants which may in turn affect the performance of an aquaculture treatment system. From a physical standpoint, evaporation can be beneficial in terms of pretreatment of the wastewater prior to discharge to an aquaculture treatment system. For example, thermal wastewaters can be cooled by evaporation so that the wastewater may become amenable to a given aquaculture system. Evapotranspiration is a biological process accomplished by plants which varies greatly among aquatic species.

The rate of evapotranspiration can be used as a gauge to measure the growth rate of an aquatic plant. For example, water hyacinths characteristically maintain a high evapotranspiration rate and are thus rapid growing plants when environmental conditions are optimal. It has been estimated that the evapotranspiration rate can be as high as 1.5 to 3 times the evaporation rate for certain aquatic plants.

4.1.5 Wind

Wind facilitates air circulation and thus increases the air/water interface and consequently, the evaporation potential. When other environmental conditions are optimal, a slight wind may aid the performance of a plant-based wastewater aquaculture system by increasing evaporation and evapotranspiration potentials. On the other hand, constant excessive winds may interfere with an aquaculture system using floating aquatic plants such as duckweed or water hyacinth by driving the plants ashore and encouraging uneven distribution of the species across the pond surface. Strong winds during low temperature periods may result in excessive wind chilling, which affects the performance of rooted aquatic species such as reeds, bulrushes and cattails. In areas where excessive wind may be a constraint, the use of wind breaks can be considered in facility design to mitigate undesirable effects. In addition, narrow or small ponds can be constructed to minimize wind effects.

4.2 Hydrogeological Variables

4.2.1 Instream Flow, Runoff and Flooding

Instream flow is an important variable when natural water bodies and natural or constructed wetlands are used as a means of treating wastewater. Instream flows vary according to the area of drainage, the amount of groundwater recharge and precipitation, and other hydrological variables. Excessive instream flow may result in erosion or even destruction of an aquaculture treatment system based on a natural water body or wetland. Insufficient instream flow may also affect the performance of an aquaculture treatment system and reduce its efficiency. In addition, seasonal fluctuations of instream flow may be well-suited for one aquatic species but detrimental to another.

Abnormally intense precipitation may result in large volumes of runoff and instream flow beyond the carrying capacity of the stream and may result in flooding. Excessive runoff and flood waters may dilute wastewater being treated by the wetland-based aquaculture treatment system and degrade the treatment performance. Flood waters can also be detrimental structurally to wetland-based aquaculture treatment systems due to the intense erosion potential. Flood trails can leave or re-deposit debris or solids on an aquaculture treatment system and render it inoperable.

Runoff waters are highly variable in amount and types of pollutants. Depending on location, runoff may contain toxic pollutants which can be harmful to aquatic plants and animals.

4.2.2 Groundwater

In areas where a significant portion of stream flow is comprised of groundwater discharge, fluctuations of the groundwater table and/or depletion of the groundwater source become an important variable in selecting and designing an aquaculture treatment system based on a natural water body or wetland. Extensive groundwater depletion may result in a lowering of the groundwater table so that it can no longer support the aquaculture treatment system. In addition, groundwater depletion may encourage the intrusion of salt water, thereby upsetting the dissolved solids concentration of the system and potentially reducing the performance of the aquaculture treatment system due to increased salinity. Groundwater availability is highly variable and should be understood fully before an aquaculture treatment system can be successfully designed and operated for a specific facility site.

4.2.3 Natural and Artifical Wetlands

Wetland environments under proper management can be used effectively for the treatment and renovation of certain wastewaters. The capability of these unique environments to treat wastewaters can be attributed to the high rate of productivity and nutrient recycling characteristic of wetland settings. Utilizing constructed or natural wetlands in the place of conventional systems can be economically and environmentally attractive. Natural wetlands that have been damaged either directly or indirectly by human activity offer potential sites for wastewater aquaculture facilities. The nutrient input and protection afforded by controlled wetlands aquaculture can help promote recovery of damaged wetlands.

There are many types of wetlands and pollutant removal efficiencies vary with type and location of wetlands. There are various classifications of wetlands and it is not the purpose of this study to select one classification scheme over another. For national needs, a classification system was developed in 1979 by U.S. Fish and Wildlife Service(5) with four long-range objectives: (1) to describe ecological units that have certain homogeneous natural attributes; (2) to arrange these units in a system that will aid decisions about resource management; (3) to furnish units for inventory and mapping; and (4) to provide uniformity in concepts and terminology throughout the United States. According to this wetland classification system, wetlands are defined as: "lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year". The U.S. Fish and Wildlife Service is preparing a list of hydrophytes and other plants occurring in wetlands of the United States. The U. S. Soil Conservation Service is preparing a preliminary list of hydric soils for use in this classifications scheme.

Basically, wetlands have been classified into five systems namely: the Marine, Estuarine, Riverine, Lacustrine, and Palustrine Systems and contain a hierarchical progression of subsystems classes, and subclasses. Modifiers for water regime, water chemistry, and soils are applied to classes, subclasses, and dominance types. Special modifiers can be used to describe wetlands and deepwater habitats that have been either created or highly modified by man or animals. This classification system with modifiers can be used to provide preliminary suitability evaluations of a particular local wetland for an aquaculture treatment system.

Soil is one of the most important physical components of wetlands. Through its depth, mineral composition, organic matter content, moisture regime, temperature regime, and chemistry, it exercises a strong influence over the types of plants that live on its surface and the kinds of organisms that dwell within it. For wetlands, the most basic distinction in soil classification in the United States is between mineral soil and organic soil.

In order to facilitate identification of natural wetlands for aquaculture treatment of wastewaters, the geographical distribution of wetlands should be known. The U.S. Fish and Wildlife Service has completed a wetlands inventory and mapping for the eastern United States and is currently engaged in similar mapping for Alaska, and eventually will produce 7½ minute wetland maps for the entire United States. The maps are too large for inclusion in this study but are mentioned for reader awareness.

Wetlands can be effectively used to treat wastewater, if they are properly selected, designed, operated, and managed. Among the many mechanisms involved in a wetland system which contribute in varying degrees to the treatment and renovation of wastewater are microbial degradation/stabilization, sedimentation, chemical precipitation, filtration, coagulation, bio-filtration into groundwater, plant metabolism, etc. Understanding these mechanisms and their effectiveness in treating wastewater by wetland aquaculture systems is important before these types of systems can be cost-effectively designed and made environmentally acceptable. As mentioned elsewhere in this study, much of the current aquaculture research is being directed toward better understanding of artificial wetland systems.

4.3 Summary

There are a wide range of variables which influence the selection, planning, design, and successful operation of wastewater aquaculture facilities. These variables are not well-documented for wastewater aquaculture. It would be helpful to future planners of such systems to have climatological, hydrogeological, and biological documentation as mentioned here in a design manual format.

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CHAPTER 5

INSTITUTIONAL AND FINANCIAL DETERRENTS TO WASTEWATER AQUACULTURE

5.0 GENERAL

Among the factors which can influence the application of wastewater aquaculture technologies are certain institutional and financial constraints. Institutional constraints include policies, regulations and laws which either limit the application of wastewater aquaculture technologies or contribute to the costs of wastewater aquaculture facilities in a way that causes them to be less competitive than other alternatives. This chapter highlights some of the more major institutional and financial deterrents to wastewater aquaculture in the United States. It should be noted that two recent reports prepared under sponsorship of the U.S. Joint Sub-Committee on Aquaculture address regulatory constraints and certain financial aspects of the aquaculture industry in the United States.(1,2) The publications focus on clean water aquaculture for the purpose of food production and give little attention to aquaculture as a wastewater treatment process. The reader is referred to them for additional information on these topics.

5.1 Clean Water Act of 1977 (P.L. 95-217)

One of the current laws which encourages the use of wastewater aquaculture is the Clean Water Act of 1977. This law provides financial incentives to authorities responsible for publically owned wastewater treatment works to investigate and implement wastewater technologies which meet certain U.S. EPA criteria under the definition of "innovative" and "alternative" (I/A) technology.

Section 201, part d(1) of the Clean Water Act promotes the construction of revenue producing facilities which reuse/recycle pollutants under the federally funded construction grants program. Aquaculture systems have demonstrated this ability. In addition, Section 201, part g(5) requires that recipients of Federal grants investigate innovative and alternative wastewater treatment techniques before additional Federal grant funding is made available for design or construction of any publicly owned treatment works (POTW). The Act provided financial incentives for I/A technologies including wastewater aquaculture prior to October 1, 1981. These financial incentives were extended by PL 97-117 and include:

- Wastewater aquaculture processes were eligible for up to 85 percent federal funding (10 percent more than conventional technologies for facilities construction);
- 15 percent cost-effectiveness preference for aquaculture processes over the least costly conventional technology; and
- 100 percent funding to modify or replace an innovative/alternative technology system in the event of failure.

Experience indicates that there has been reluctance by various State regulatory agencies with approval authority for wastewater facilities to accept designs for facilities which incorporate innovative or alternative technologies, including aquaculture. Although P.L. 95-217 provides certain incentives for use of I/A technologies, engineers are often reluctant to propose such systems because they must then engage in a complex project approval process and often encounter delays in obtaining approvals. This process often involves educating regulatory agency staff and conformance with various procedures for obtaining special exceptions and exemptions, both of which tend to deter engineers.

Additionally, engineers who are aware of aquaculture and other I/A technologies are frequently reluctant to suggest or design such technologies to potential increased exposure to design risk and legal claims. Although EPA grant funded projects offer replacement guarantees in the event of facility failure, the accompanying administrative difficulties and costs are a significant deterrent. Experience has shown also that municipalities and other public bodies are often reluctant to accept recommendations for I/A technology, such as aquaculture, when it is perceived that they may be "guinea pigs" for something that is relatively untested.

P.L. 95-217 also recognizes the value of facilities which culture plants and fish for beneficial uses other than wastewater treatment and provides for National Pollutant Discharge Elimination System (NPDES) permits for such facilities.

5.2 National Aquaculture Act of 1980 (P.L. 96-362)

The National Aquaculture Act of 1980 makes it a national policy to encourage development of aquaculture in the United States.(4) The Act calls for a National Aquaculture Development Plan to be used in overcoming many of the obstacles encountered in aquaculture development. The Act authorizes federal funds for aquaculture development to be allocated by Congress and the Office of Management and Budget.

The Joint Subcommittee on Aquaculture (under the Federal Coordinating Council of Science, Engineering, and Technology) was formally introduced in this Act to increase the overall effectiveness and productivity of federal aquaculture research, technology transfer, and assistance programs. Currently, three panels comprise the Joint Sub-Committee: Economics, Science and Technology, and Education and Training.

5.3 Food and Drug Cosmetic Act (FDCA)

The Federal Food and Drug Cosmetic Act (FDCA)(15) and Fair Packaging and Labeling Act(16) were promulgated to protect humans and animals from consuming unhealthful foods. These regulations would apply to any by-product of a wastewater aquaculture facility that is intended for human consumption. The regulations prohibit the distribution of articles that are adulterated (unsafe, filthy) or misbranded (false or misleading advertising). The Delaney amendment to the FDCA bans any additive that induces cancer when ingested by human or animals.

One serious public health concern is the bioaccumulation of heavy metals and toxic substances in both plants and animals reared in wastewater aquaculture facilities. Another is the transfer of viruses and disease through other microorganisms present in wastewaters that become associated with harvested by-products. By severely restricting the ultimate disposition of wastewater aquaculture by-products, the potential economic benefits are also diminished and this may be sufficient to deter selection of aquaculture for a particular application. At best, the current Food and Drug laws severely limit potential re-use and recycle applications of aquaculture by-products for human use.

An example of a project affected by these restrictions is the Benton, Arkansas fish aquaculture treatment facility. Neither the FDA nor other State and local health agencies have allowed distribution of fish reared at this facility for human consumption although the fish were grown under highly controlled conditions.(17)

5.4 Sludge Management Regulations

The U.S. EPA is developing regulations which address distribution and marketing of sewage sludge products under 40 CFR Parts 257 and 258. The EPA has recognized a need to protect the public from toxic substances and pathogens that may be present in sludges and sludge by-products that are distributed and marketed. In addition, EPA is attempting to encourage resource recovery through beneficial uses of sludges and sludge by-products as fertilizers and soil conditioners by controlling unsafe sludge distribution and marketing practices. Although the regulation does not specifically address wastewater aquaculture by-products, such as fish, fish emulsions, composted plant materials, etc., which have potential uses as fertilizers and soil conditioners, these products are analogous to sludges from conventional treatment facilities. The regulations govern the placement of stabilized sludge in acceptable areas and provides minimum quality requirements for sludge that is to be landspread on food chain cropland. The quality requirements are in terms of cadmium, polychlorinated biphenols (PCB's), lead and pathogenic organisms.

The regulations do not apply to agricultural waste such as manures and crop residues returned to the soil as fertilizer or as a soil conditioner, but do apply to all other disposal of agricultural wastes. It is not clear whether this exclusion would also apply to wastewater aquaculture operations.

If industrial wastewaters are treated in aquaculture systems for the removal of phenols or trace heavy metals as have been demonstrated with water hyacinth systems and systems which cultured shellfish, the by-products may contain unusually high concentrations of these substances, thereby categorizing them as toxic or hazardous wastes. Complex regulations governing such wastes were promulgated under the Resource Conservation and Recovery Act of 1976.(9,19) If the solid waste by-products are considered hazardous, then regulations concerning the generation, storage, transportation, and disposal may also apply.

Certain exemptions are granted for hazardous sludge if "beneficial landspreading" is used. However, the cadmium, lead, PCB, and pathogen quality parameters still apply for landspreading on foodchain cropland.

5.5 Wetlands Policies and Other Land Use Restrictions

Executive Order 11990, issued in 1977, outlined a strong national policy for the preservation of wetlands and required that Federal agencies not undertake or assist in construction projects in wetlands unless there was no alternative. Section 404 of the Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500) and Clean Water Act of 1977 (P.L. 95-217) made the U.S. Army Corps of Engineers responsible for issuing permits to place dredged or fill materials in wetlands. Wastewater aquaculture projects which propose the use of natural wetlands may meet opposition under these policies and laws and may either be denied permits or face significant opposition and delay. At a minimum, wastewater aquaculture projects in natural wetlands face detailed environmental scrutiny in order to prove that their benefits will outweigh any adverse environmental consequences. In many instances, it is believed that the prospect of prolonged delays in obtaining permits including environmental impact assessments, and the administrative complexities of the permit procedures would be more than sufficient reason for planners, engineers and administrators to elect options other than aquaculture in natural wetlands.

It should be noted, however, that wastewater aquaculture has a potential application in restoring damaged wetlands and proposals for facilities in damaged wetland areas may be viewed as significantly more beneficial than those proposed in healthy natural wetlands. For example, the State of Florida has adopted regulations and procedures to encourage experiments which lead to development of low energy approaches to advanced treatment of agricultural, industrial and domestic wastes and encourage conservation of wetlands and fresh waters.(14) By process of special exception, a permit may be obtained in Florida to discharge pollutants to a wetlands ecosystem under the following conditions:

- Adequate demonstration of waste assimilation
- Assurance that discharge does not adversely affect public health
- Public access to the wetlands is restricted
- Waters are not used for recreation
- Adequate demonstration that potable water supplies are protected
- Non-interference with continuous waters
- Experiment incorporates valid controls and monitoring of long-term ecological effects.

This type of policy, if adopted by more states, could serve to advance wastewater aquaculture technology and enhance public acceptance.

5.6 Species Restrictions

The Grass and Plants Interstate Shipment Act (P.L. 874) restricts the transport of certain species among states. Water hyacinths, one of the typical plants cultured in wastewater aquaculture systems has become a nuisance species in many Gulf Coastal states and its shipment to other states is restricted.(13) There are also restrictions on import of certain non-native animal species such as the grass carp because of uncertainty regarding its ability to out-compete other native species and become a potential pest. While some restricted plants and animals may be of potential benefit in wastewater aquaculture uses, loss of control of such species can have adverse consequences on public welfare.

5.7 Land and Water Use Restrictions

Under the EPA Construction Grants Program, wastewater facilities cannot be designed within designated 100-year floodplains without special provisions to protect the facilities against flood damage and discharge of untreated wastes. Wetlands facilities, by their very nature are sited and constructed in areas subject to flooding and would be in conflict with these Agency rules. Although Section 318 of the Clean Water Act specifically allows the granting of permits for aquaculture facilities in navigable waters, it is logical to expect that such facilities would face strong local opposition. It is believed that a Section 318 discharge permit has yet to be issued for an aquaculture facility.

5.8 Financial Considerations Influencing Wastewater Aquaculture Development

One of the more serious problems facing all wastewater treatment projects, aquaculture and conventional, is funding. The U.S.EPA Municipal Construction Grants Program has benefited many publically owned treatment facilities but does not provide assistance to solve industrial or agricultural wastewater problems. The EPA construction grants program has funded up to 85 percent of the construction cost of wastewater projects incorporating innovative/alternative technologies with the state and local share being 15 percent. This program has funding policies that encourage wastewater aquaculture because of opportunities to conserve energy and recycle wastes. There is a particular financial incentive due to the fact that grant funds are only available for design and construction of facilities while the burden of operating costs is always a local matter. The incentive to use of aquaculture stems from a comparatively low energy costs which must be borne locally for the life of the facilities.

Privately owned wastewater treatment facilities, such as an industrial treatment plant, must be financed by the industry. In certain cases, the Federal Small Business Administration can assist small businesses with the financing of wastewater facilities that are required as the result of water pollution control laws.(20) However, for technologies like aquaculture which are relatively untested, there may be a lack of confidence by such funding sources and a tendency to use more conventional approaches. Additionally, smaller businesses may be reluctant to commit the comparatively greater time and financial resources that would be necessary to gain approval of wastewater facilities which are still considered experimental.

The Farmers Home Administration has, in the past provided loans and grants for waste disposal facilities in rural area communities (less than 10,000 population) if these communities can not obtain reasonable credit from other sources.(20) The loans are typically for 40 year terms; grants can cover up to 75 percent of eligible project costs. The Economic Development Administration can help fund public works in areas of high unemployment and where economic growth is lagging.(20)

The prospect of selling wastewater aquaculture by-products has potential attractiveness and may at some future time become more of an incentive to use of aquaculture processes. For example, the Woods Hole Oceanographic Institute tested a marine aquaculture system using secondary wastewater as a nutrient source for a plankton-bivalve mollusk food chain. Reported estimates of production indicate that a town of 50,000 persons with a 126 acre wastewater aquaculture treatment system could grow over 900 tons of oysters annually with an estimated value of over $85 million as a luxury food.(22) Fish raised to remove algae from waste treatment lagoons at Quail Creek, Oklahoma have been estimated to be able to provide a potential return of approximately 2 cents/1,000 gallons of wastewater treated.

However, such returns are only "potential" at this time due to previously discussed restrictions which prevent human consumption of waste-grown aquatic organisms. Other users are constrained by processing requirements, and still others may provide ready economic returns with little or no processing requirements. By-product processing requirements and potentials are further discussed in Chapter 8.

5.9 Summary

There are a number of Federal and State policies, laws, and regulations which are intended to encourage low-energy wastewater systems and systems which have a potential for recycling resources. The most important of these are the Clean Water Act and the National Aquaculture Act which favor wider implementation of wastewater aquaculture. Other laws, the most significant of which is the Food, Drug, and Cosmetic Act are considered restrictive of wastewater aquaculture due to restrictions on by-product utilization, which if amended, could provide significant financial incentive for more widespread application of the technology.

Wastewater aquaculture cannot be fully exploited for its potential benefits until there is a coordinated effort to gain exceptions to current restrictions. Under appropriate controls on by-product quality and stringent monitoring of wastewater aquaculture operations, it is believed that the technology can fulfill a two-fold purpose of producing clean water while also providing safe, acceptable, marketable by-products.

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CHAPTER 6

DESIGN AND OPERATION OF AQUACULTURE TREATMENT FACILITIES

6.0 INTRODUCTION

An extensive study report (National Operation and Maintenance Cause and Effect Survey) by the U.S. EPA, indicated that the majority of existing conventional wastewater treatment plants can not meet optimal levels of performance as intended. This performance inefficiency was attributed to two factors: (1) general lack of process understanding by operations personnel leading to improper system operation and maintenance, and (2) design deficiencies in the areas of system flexibility, system reliability and failure to account for variables such as infiltration and inflow. These problems with conventional treatment plants would be duplicated in wastewater aquaculture projects, if not adequately addressed in the early stages of development.

As with any wastewater treatment facility, the successful implementation of aquaculture treatment systems is highly dependent on proper design and operation. However, due to the fact that there have been relatively few full scale facilities from which actual field experience in use of aquaculture wastewater treatment systems can be gained, and due also to lack of experience and documentation of the ecological and biological complexity of these systems, guidelines for optimal system design and operation are still in an early developmental stage.

Lack of information about system design forces regulatory agencies and engineers to apply safety factors which must be excessively large until data becomes available to better optimize designs. This leads to an unfavorable situation with regard to facility costs for construction and operation.

Therefore, an identification of technical deficiencies and restraints on wastewater uses for aquaculture was considered important to reveal research needs that, when met, will allow more cost-effective designs.

This Chapter addresses design and operation considerations for wastewater aquaculture facilities.

6.1 Design Considerations

Design of a successful aquaculture treatment system is based on a number of design considerations which can be grouped into the following chronological phases:

- Process evaluation and selection of aquatic species
- Treatment process train development
- Treatment process design and process control
- Cost-effectiveness analysis
- Detail system design
- Construction cost estimate
- System operation, maintenance, and management
- Construction inspection and management

6.1.1 Selection of Aquatic Species and Process Evaluation

Aquatic processing units (APU) can be used alone to treat raw wastewater directly or as part of the process train in combination with more conventional wastewater treatment processes. The selection of an APU including selection of aquatic species is a complex task which should abide certain scientific and engineering principles. Unlike conventional treatment systems, the criteria for APU selection are not widely published nor as readily available for aquaculture treatment systems, a factor which complicates the selection process. Considerations in the selection of an APU may include:

- Wastewater pretreatment and post-treatment requirements
- Species naturally occurring and locally available
- Adaptability of species to wastewater under investigation
- Vulnerability or susceptibility of the species to climatic factors
- Vulnerability or disease susceptibility of the species to wastewater parameters (both conventional and priority pollutants)
- Seasonal and annual productivity of the species
- Site specific requirements

The most favored candidate species for a contemplated aquaculture treatment system are those which are most adaptable to the wastewater, tolerant to all wastewater parameters without exotic pretreatment, productive on a year-round basis, least constrained by site conditions, and require the least post-treatment attention. Once the candidate species are selected, the type of APU (plant, animal, combined, or wetland process) can be preliminarily determined.

Since most, if not all, of existing aquaculture treatment systems are experimental it is believed that the selection of aquatic species has been largely influenced by each researcher's knowledge about available species, species characteristics and possibly even the funding potential for experimentation with a particular species. The rationale behind the selection of species, in general, has not been well-documented.

The history of aquaculture treatment technology development has been one which evolved from using aquatic species for renovation of treated effluent to eventual use of various species for treatment of raw sewage. Most species tested to date have been used to treat municipal wastewater. The lack of criteria with which to screen and select candidate species undoubtedly contributes to limiting wider application of aquaculture treatment systems, as compared to conventional treatment systems. A systematic approach to selecting species is needed and is yet to be developed.

Also, review of the past history of wastewater aquaculture has indicated that great emphasis has been placed on water hyacinths as potential aquatic species for aquatic processing units. Due to severe geographical constraints (i.e., continual water hyacinth growth is very limited geographically to areas such as southern Texas and Florida) and institutional constraints (i.e., water hyacinths are considered a nuisance species whose import is prohibited by a number of states), water hyacinths have very limited application for aquaculture treatment systems. The most recent trends, as a result of more technical data being made available, are toward use of rooted emergent aquatic plants including reeds, bulrushes and rushes as the most suitable candidates for aquaculture treatment systems. Additional studies are needed, especially in the central and northern states, to confirm the widespread suitability of emergent plants for wastewater aquaculture.

In reviewing a wide variety of studies on the feasibility of various aquatic species for aquaculture treatment systems it was noted that most studies were conducted under controlled environmental conditions (e.g. a greenhouse) and on a short-term basis. Although, many experiments provided encouraging results, the performance of most aquatic species under low temperature conditions has not been satisfactorily addressed nor have cost-effective mitigative measures against the adverse effects of low temperatures been developed. Additionally, aquaculture treatment technology researchers have tended to place study emphasis on liquid treatment aspects and the solids disposal problems which accompany various species are often neglected. Biomass removal, utilization, and disposal aspects for various species should be addressed as part of species selection.

6.1.2 Treatment Process Train Development

The term aquatic processing units (APU's) has been recently introduced by Stowell, et al.(1) The APU concept avails the potential for logical construction of alternative aquaculture treatment process trains for a specific project.

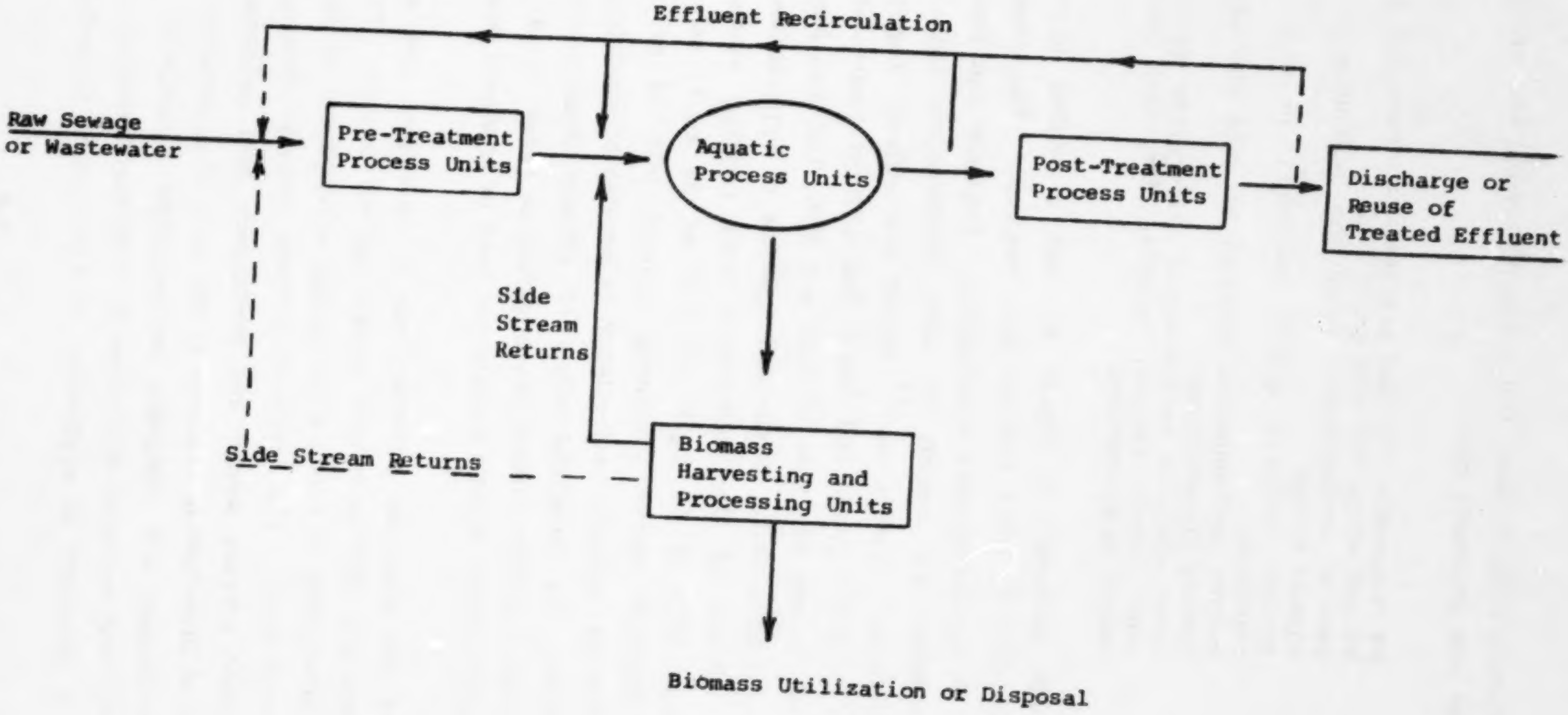
The type of APU and species preliminarily selected dictates the treatment process train. A process train defines the interrelationship between unit process elements which are further developed in the treatment process design. Basically, an aquaculture treatment process train should consist of the following:

- preliminary treatment processes compatible with the APU's contemplated
- appropriate number and types of APU's to achieve the level of treatment required and to provide consistent treatment on a year-round basis
- compatible post-treatment processes to condition the treated effluent with the objectives of meeting necessary discharge permit conditions
- biomass harvesting, processing, and handling process
- side liquid streams which have to be fed back to the main liquid processing stream.

As indicated in Figure 6.1 an aquaculture treatment process train may, in general, consist of pretreatment units, APU's, post-treatment units, effluent

Figure 6.1

SIMPLIFIED FLOW DIAGRAM OF TYPICAL
AQUACULTURE TREATMENT SYSTEMS


Effluent Recirculation
Raw Sewage
or Wastewater
Pre-Treatment
Process Units
Aquatic
Process Units
Post-Treatment
Process Units
Discharge or
Reuse of
Treated Effluent
Side
Stream
Returns
Side Stream Returns
Biomass
Harvesting and
Processing Units
Biomass Utilization or Disposal

disposal/utilization options, and solids processing and utilization methods. Each of these unit processes must:

- be compatible with unit processes upstream and downstream
- be compatible with site conditions
- provide environmental conditions conducive to the growth of the aquatic species
- produce effluent quality sufficient to meet discharge or reuse standards
- relieve environmental stresses so that the aquatic species do not become disease-prone
- have adequate environmental safe-guards against such problems as odor, insect vectors, rodents, fire, and other public health and safety considerations.

Although indicated in Figure 6.1 for a typical system, the question of recirculation in APUs has not been resolved. The great majority of existing APUs do not incorporate recirculation. Englande and Tridech(2,3) were able to demonstrate the benefit in APU performance and stability by effluent recirculation. Vanhurizan(4) tested the effluent recirculation concept using water hyacinth ponds and found that effluent recirculation not only improved effluent quality in terms of BOD and TSS, but also increased the capacity of the treatment unit. Recirculation ratios of approximately 3 to 6 were used. The effluent of the recirculation unit treating secondary effluent had an average BOD of 15 mg/l and TSS of 30 mg/l, as compared to a similar once-through system producing average BOD of 58 and TSS of 69 mg/l. Apparently, effluent recirculation is capable of maximizing process throughput. However, the beneficial effect of effluent recirculation remains a technical question awaiting further investigation in order to advance the APU concept, especially when aquatic animals are used in treatment systems.

Once the treatment process train is developed, the water quality conditions before and after each unit process can be defined. This information can then be interpreted to produce the optimal arrangement of the unit components of the process train. The treatment process train so developed forms the basis for detailed process design and preliminary cost estimates. Unfortunately, very limited literature is available in the area of aquaculture treatment process train development and designers contemplating aquaculture treatment systems are faced with technical difficulties in obtaining literature. This situation in itself is a deterrent to application of aquaculture technology. In extreme cases, designers may need to conduct pilot studies in order to finalize a treatment process train concept, and this too is a deterrent.

6.1.3 Treatment Process Design and Process Control

Once the treatment process trains are developed, each process element can be determined. Treatment process design yields information necessary for preliminary system cost estimates and parameters essential in detail system design. From available literature it is apparent that parameters affecting aquaculture treatment process design are not well-understood. Most of the available literature is rather localized and applicable to the specific localities where the experimental or pilot systems were conducted.

Considerations necessary in developing the process design of an APU. have been identified by a number of researchers and designers. They can be grouped into the following categories:

- pollutant loading rates to an APU
- wastewater characteristics and pretreatment requirements
- physical and chemical parameters
- environmental parameters
- biomass handling
- process start-up and acclimatization requirements

Pollutant loading rates determine the physical dimensions, number of stages, and redundant number of APUs and the flow distribution pattern in an APU. Depending on the level of treatment to be achieved by an APU, the pollutant loading rates to be considered should include:

- localized and overall BOD loading rates
- localized and overall TSS loading rates
- localized and overall TKN loading rates
- localized and overall loading rates of other pollutants
- seasonal productivities of the aquatic species
- tolerance levels of the aquatic species to various pollutants (e.g., phenol, heavy metals, etc.) to be removed by the APU
- accumulation rate of phosphorus
- accumulation rate of volatile and inert solids

Certain physical and chemical parameters also affect some basic requirements of an APU. The major considerations in terms of physical and chemical parameters should include at minimum:

- hydraulic loading rates, and maximum horizontal transport velocity to prevent scouring or re-entainment of bottom sediments
- control of flood and area-wide run-off
- sludge storage volume required in an APU
- temperature and auxiliary heat input requirements
- diurnal dissolved oxygen level and aeration requirements
- pH
- diurnal alkalinity.

6.1.4 Available Design Criteria

Design criteria regarding process designs of aquaculture treatment systems have been proposed and used by a number of researchers. Some of the criteria are summarized in Table 6.1. It should be noted that these design criteria have been applied to a limited number of systems. The geographical transferrability of these design criteria to project sites other than those where the specific research was conducted has not been evaluated and presents an area for further investigation and research.

Most of the proposed design criteria or parameters tend to be related to steady-state equilibrium conditions of aquaculture treatment systems. In fact, most aquaculture treatment systems are greatly influenced by a number of environmental factors such as temperature, (especially freezing), wind, soils, local ecologic elements, and other climatic elements. Aquaculture treatment systems however rarely perform under steady-state conditions, and are instead, non-steady state and dynamic in nature.

Few published process design procedures attempt to account for the dynamic variability of aquaculture treatment systems. In dynamic aquatic process units, there are often rate-limiting reactions which collectively determine the overall performance of an aquaculture treatment system. Methods by which the reaction rates of these rate-limiting reactions can be controlled to maintain or improve the performance level of an aquatic process unit are not well-developed. Due to the lack of satisfactory solutions to these types of technical problems, design of aquaculture treatment systems must by necessity

Table 6.1

PROPOSED DESIGN CRITERIA FOR AQUACULTURE TREATMENT SYSTEMS

Type of Treatment	Water Hyacinth		Duckweed			Reeds/Bulrushes (Pope,et al)						Polyculture	
	(Stowell et al) 2° Treatment of Raw Sewage Without Nutrient Removal	3° Treatment of 2° Effluent With Nutrient Removal	(Wolverton) 2° Treatment of Raw Sewage			2° Treatment of Raw Sewage			3° Treatment of Raw Sewage			3° Treatment of 2° Effluent	
			First Basin	Second Basin	Overall System	Reeds Trench	Bulrush Trench	Overall System	Reeds Trench	Bulrush Trench	Overall System	Henderson	Dinges
Unit Water Surface Area (acres/MGD)	40-50	12	--	--	28	4.1	4.1	8.2	4.1	4.1	8.2	26-36	6.2
Water Depth (ft)	4-5	3-4	--	--	5-8	4	2.5	--	4	2.5	--	3.9-4	2
Detention Time (days)	40-50	5-10	36	21	57	0.5	2	2.5	0.5	2	2.5	35-47	5.3
BOD$_5$ Loading (lb/ac-day)	20-30	50-60	84	26	54	380	180	190	36	23	18	6.5-7.8	27.1
TSS Loading (lb/ac-day)	--	--	86	78	55	400	110	200	38	20	19	8.7-23	47.4
TKN Loading (lb/ac-day)	--	2.6-17.4 (avg. 13.4)	--	--	--	80	60	40	30	20	15	1.6-2.3	9.4
Total P Loading (lb/ac-day)	--	0.8-4.3	--	--	--	46	32	23	29	25	15	0.7-2.6	--
Individual Basin Area (ac)	1-2	1-2	--	--	--	--	--	--	--	--	--	--	--
Length : Width Ratio	3:1	3:1	--	--	--	6	12	--	6	12	--	--	--
Width for Ease of Harvest (ft)	25-30	25-30	--	--	--	12	12	12	12	12	12	--	--
Water Temperature (°F)	50	68	Warm Weather			Warm Weather			Warm Weather			Warm Weather	Warm Weather
Dual or Multiple Systems	Essential; 2-3 Cells in Series	Essential; 2-3 Cells in Series	Essential; 2 Cells in Series			Essential; Multiple Cells In Series & Parallel			Essential;Multiple Cells In Series & Parallel			Essential	Essential;5 Cells in Series
Mosquito Control	Essential (use Gambusia)	Essential (use Gambusia)	Not Reported			Not Reported; Not Practical In Trenches			Not Reported; Not Practical In trenches			Not Reported	
Initial Aeration	Essential	Essential	Not Reported			Not Necessary			Not Necessary			Essential, Especially in Fish Ponds	
Solids Breakthrough Velocity (ft/hr)	Not Reported	Not Reported	Not Reported			Not Reported			Not Reported			Not Reported	2.5-2.9 ft/hr
Productivity (wet tons/ac-yr)	100-1,000	100-1,000	300			700-66,000			7,000-66,000			--	
Harvest of Biomass	Essential	Essential	Essential			Essential			Essential			Essential	
Harvest Frequency and Criteria	Not Reported	Not Reported	Not Reported			Not Reported			Not Reported			Function of Growth Rates	

Table 6.1 (cont'd)

Type of Treatment	Water Hyacinth (Stowell et al) 2° Treatment of Raw Sewage Without Nutrient Removal	Water Hyacinth (Stowell et al) 3° Treatment of 2° Effluent With Nutrient Removal	Duckweed (Wolverton) 2° Treatment of Raw Sewage First Basin Second Basin Overall System	Reeds/Bulrushes (Pope,et al) 2° Treatment of Raw Sewage Reeds Trench Bulrush Trench Overall System	Reeds/Bulrushes (Pope,et al) 3° Treatment of Raw Sewage Reeds Trench Bulrush Trench Overall System	Polyculture 3° Treatment of 2° Effluent Henderson Dingee
Prerequisite Removal of Gross Solids, Oil/Grease	Yes	Yes	Yes	Yes	Yes	Yes
% Aquatic Plant Coverage to Supress Algae	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Sludge Storage Volume Requirements	Yes	Yes	Yes	Not Reported	Not Reported	Yes
Diurnal D.O. Problem	BOD Dependent	Not Severe	BOD Dependent	Unknown; BOD Dependent	Unknown; BOD Dependent	BOD Dependent
Diurnal Alkalinity Problem	No	TKN Dependent	No	Unknown	Unknown	Unknown
Effluent Recirculation Required	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Threshold Toxicity of Various Pollutant(s) to Species	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Stocking Requirements for Initial/Seasonal Operation	Not Suggested	Not Suggested	Not Suggested	Not Mentioned	Not Mentioned	Not Suggested
Acclimation Period	Not Suggested	Not Suggested	Not Suggested	Not Mentioned	Not Mentioned	Not Suggested
Sludge Removal Requirements	Not Suggested	Not Suggested	Not Suggested	Not Mentioned	Not Mentioned	Not Suggested
Biomass C:N:P Ratio	100:6.5:1.4	100:6.5:1.4	100:12.8:2.2	--	--	--
Biomass Water Content (% by Weight)	95%	95%	95%	--	--	--
Biomass Dewatering Required	Yes	Yes	Yes	Yes	Yes	--
Attempted Biomass Disposal or Utilization Methods	Landfill Compost Fertilizer Soil Conditioner Methane	Landfill Compost Fertilizer Soil Conditioner Methane	Landfill Compost Fertilizer Soil Conditioner Methane	Landfill Compost Fertilizer Soil Conditioner Methane	Landfill Compost Fertilizer Soil Conditioner Methane	Landfill Food Supplement Food
Greenhouse or Supplemental Heat for Overwintering	Yes	Yes	Yes	Yes	Yes	Yes
Nitrogen Removal (lb/ac-yr)	700	700	600	300-700	300-700	--
Phosphorus Removal (lb/ac-yr)	160	160	180	300-700	300-700	--
Removal of Refractory Organics and Trace Metals	Yes; Rate Unknown	Yes;Rate Unknown	Yes; Rate Unknown	Yes; Rate Unknown	Yes; Rate Unknown	--
Runoff Diversion and Flood Control Required	Yes	Yes	Yes	Yes	Yes	Yes

be conservative. This is a factor which is considered limiting to more widespread application of the technology. This is especially true of natural wetland-based treatment systems, for which the majority of the removal mechanisms are either not well-understood or have not been quantified.

To address the dynamic nature of aquatic processing units for aquaculture treatment system design, several analytical models have been suggested. Gee and Jenson(30) proposed the use of a BOD equation, and an equation for sizing of a conventional treatment lagoon to determine the preliminary size of a water hyacinth treatment system for both summer and winter conditions. An adjustment is then applied to the preliminary sizes by considering the nutrient removal rates of typical water hyacinth pond systems.

King(31) examined the alkalinity requirements and limitations on aquaculture treatment systems where the treatment objective was nutrient removal. King indicated the diurnal dynamic nature of alkalinity in the water column which is regulated by availability or shortage of inorganic carbon. Shortages of inorganic carbon can have a great impact on aquatic plants. The three sources of inorganic carbon available to photosynthetic aquatic organisms are: respiratory carbon dioxide from heterotrophic aquatic organisms and microorganisms, atmospheric recarbonation, and the carbonate-bicarbonate alkalinity reservoir within an aquatic system. Of these three sources, the only significant reserve of inorganic carbon is contained within the alkalinity which supplies inorganic carbon to aquatic phytoplankton for photosynthesis in enriched waters. Withdrawal of carbon dioxide by aquatic plants causes a change of the system chemistry, most of which favors physical-chemical removal of phosphorus, metals, and depending on the form present, nitrogen.

During daylight hours, aquatic plants withdraw the free carbon dioxide from the water at a rate greater than can be replenished by atmospheric recarbonation and respiratory sources, causing a net depletion of bicarbonate and hydrogen ion concentrations and an increase in pH. This increase in pH results in formation of calcium carbonate precipitates which trigger some physical-chemical removal mechanisms and favor removal of phosphorus, ammonia and heavy metals. Ammonia can become partially volatilized due to the high pH environment. At night, the process is reversed. With this hypothesis, King suggested the following analytical equation for calculating nitrogen removal rate:(31)

$$N_t = N_o C^{-0.03t}$$

Where:

N_t = total nitrogen concentration (mg/l) at time t.

N_o = initial total nitrogen concentration (mg/l) at time zero.

t = time (days)

The kinetic nitrogen removal coefficient (0.03) is dependent on water temperature and the aquatic species used. King was able to demonstrate that nitrogen removal by an aquaculture treatment system was predominated by volatilization of ammonia, nitrification and denitrification by microbial chemotropic reactions, and to a lesser degree by plant uptake. Whether this hypothesis is valid requires in-situ and real time monitoring results of carefully designed experimental systems.

King also indicated that removal of phosphorus is affected by dynamic pH variations, and suggested that total phosphorus concentrations exceeding 40 mg/l might be toxic to water hyacinths. Whether long-term operation of an aquaculture treatment system will result in the pooling of phosphorus in the bottom sediments to a saturation level beyond which significant removal of phosphorus is eliminated and break through of phosphorus ensues is a debatable issue. The same concern may be raised for nitrogen removal in an overloaded aquaculture treatment system.

As discussed in Chapter 2, Englande and Tridech(2,3) were able to demonstrate that the removal kinetics of various aquaculture treatment systems for various pollutants (including BOD, boron, arsenic, and heavy metals) follow certain mathematical models including a first order kinetic model and a composite exponential kinetic model. In addition, the uptake kinetics follows closely a one compartment model or a two-compartment model. Unfortunately, these experiments were conducted under favorable temperature conditions in a greenhouse. How these kinetic coefficients vary with water temperature remains undefined and requires further research.

In order to make aquaculture treatment systems acceptable, they must be designed with adequate considerations to public health and environmental protection. Among the environmental considerations are:

- control of disease vectors (e.g., insects especially mosquitos, rodents, birds, etc.)
- control of odor
- protection of health and safety of operators
- control of runoff from entering the treatment system
- protection of the system from flood damages
- protection of groundwater resources from contamination by the treatment system as a result of infiltration and short-circuiting of wastewater to the groundwater systems
- control of erosion by avoiding excessive slopes and bare ground surface
- control of freezing problems, when necessary
- control of plant growth to minimize the potential of becoming an environmental nuisance (such as clogging of waterways by spreading of water hyacinth).

Mitigative measures to avoid adverse environmental effects have been casually suggested in the literature.(32) In fact, mitigative measures, in most cases, are site specific and should be developed and evaluated locally for the aquaculture treatment processes contemplated. It is suggested however, that certain minimum guidelines should be made available to guide and assist environmental planners and designers of aquaculture treatment systems.

The processing and handling of biomass produced by an aquaculture treatment system is an integral part of the system and should be designed in a manner that is compatible with other portions of the system. Depending on the treatment goal, harvesting of biomass from aquaculture treatment systems can be essential to maintaining optimal treatment efficiency and optimal growth of aquatic species in the system. Unfortunately, most of the available literature fails to draw conclusions regarding the amount of harvest in each harvesting period, the frequency of harvest, time of harvest, and method of harvesting. Additional criteria for determining harvest volume, frequency and method needs to be developed.

Aquatic species, especially aquatic plants, contain tremendous amounts of water. In order to render the biomass suitable for beneficial uses, it must be dewatered and sometimes dried. The most economic means of biomass dewatering and drying are still in a developmental stage. Additional discussion of biomass processing is presented in Chapter 8.

In order to have a successful aquaculture treatment system, the design must provide adequate features in the system to facilitate process system start-up. During the initial or seasonal start-up of a system, design features must be provided for transplanting or stocking the aquatic species, acclimating the species (whether juvenile or adult) to the wastewater to be treated, and promoting the growth at various growth stages for optimal utilization of the system. Various design features should be provided to ensure a consistent level of treatment of the wastewater when components are being repaired or during initial or seasonal system start-ups. Literature regarding system acclimatization and start-up is extremely limited. This presents a major constraint on the wider application of aquaculture treatment technology.

In addition, what elements are essential in terms of process quality monitoring; and what feedback mechanisms should be made available to allow future design and operational changes to maintain quality assurance and quality control are some of the technical questions for which answers should be incorporated into the process design. Among the technical questions which remain to be answered are:

- For process control, is simply sampling system influent and effluent adequate?
- What additional monitoring points and parameters are needed in order to assure consistent high level of performance?

- If a system is designed to remove phosphorus, is it necessary to sample and monitor phosphorus content of bottom sediments and water columns in an APU?
- Is it necessary to monitor sludge blanket level in an APU, and what is the frequency desirable?
- Is groundwater quality monitoring necessary and how extensive should the system be to detect any degradation of groundwater resources?
- Is an odor detection system necessary and how extensive should the system be?
- What are the minimum and optimal environmental monitoring systems and control measures to be incorporated into the design of an APU to minimize odor, disease, mosquito, and other potential environmental nuisance problems?

6.1.5 Cost-Effectiveness Analysis

Prior to adoption of an aquaculture treatment system, a cost-effectiveness analysis including all costs and environmental considerations should be performed. Comparable conventional treatment alternatives should be analyzed along with prominent aquaculture treatment alternatives in the cost-effectiveness analysis. Preparation of a thorough cost-effectiveness analysis would definitely enhance the implementability (i.e., public acceptance) of a contemplated APU system where such a system is demonstrated cost-effective.

Cost-effectiveness analysis procedures for aquaculture treatment systems are essentially the same as those used for conventional treatment systems. However, unlike conventional systems, some of the cost items (e.g., costs for transplanting species, acclimating species, harvesting, etc.) have not been well documented. Judgemental pricing decisions are necessary at this stage in the development of aquaculture treatment technologies and difficulties encountered in assigning a monetary value to specific APU components may become a significant deterrent to final implementability. Adequate disclosure and assessment of these items in qualitative rather than monetary terms would help the implementation of an APU system. However, procedures, approaches, or methodologies for assessing these intangible items are simply not available and require additional investigation. These non-monetary items may include but are not necessarily be limited to:

- Compatibility of an APU system with the candidate sites and their surrounding land uses.
- Environmental issues (odor, diseases, food chain control, public health and safety, etc.)
- Long-term and short-term reliability of APU systems especially in the areas of long-term local ecological changes resulting from implementation of APU systems.

Additional discussion of the cost-effectiveness aspects of APU systems is provided in Chapter 7.

6.1.6 Detail System Design

The most critical design problems should be addressed completely in the process design of an APU. Detailed system design is simply a translation of all process design computations into physical or structural requirements. These requirements fall under several groups:

- hydraulic requirements
- mechanical requirements
- electrical requirements
- instrumentation and laboratory requirements
- structural requirements
- site requirements

Detailed system design should conform to the concepts established in the process design phase of an APU system. The spatial, hydraulic, and other physical arrangements determined in detailed system design simply fulfill all of the requirements identified and quantified in the process design phase with an adequate margin of safety.

Detailed system design is relatively an easier task compared to process design of an APU. For low-technology systems, specifications for electrical, mechanical, and structural engineering items should be available. Site plans for aquaculture treatment systems can be developed based on available site planning procedures and codes applicable in the application area, except for natural wetland treatment systems, for which site planning elements have not been delineated and require further research efforts.

6.1.7 Construction Cost Estimates

Once the detail system designs are completed, construction cost estimates can be prepared based on local prevailing labor and material rates, and quotations from equipment manufacturers. The only area of weakness in construction cost estimates may be the costs of biomass harvesting equipment. Additional investigation efforts may be needed in this area to enable designers to obtain a more accurate cost estimate.

6.1.8 System Operation, Maintenance, and Management

There is a very limited knowledge and recorded experience in operation and maintenance (O & M) of aquaculture treatment systems due to the newness of the concept. In general, an appropriate O & M system of an aquaculture treatment system should include the following elements:

- A comprehensive O & M manual
- A proper management organization of personnel with necessary trades and skills in managing aquaculture treatment technology

An O & M manual should address the following aspects of an aquaculture treatment system:

1. Purpose and objectives of the aquaculture treatment system
2. Detailed description of all unit processes, their capabilities and limitations
3. Detailed description of all equipment, and instruments; and their intended uses, capabilities and limitations
4. The relationship between unit processes
5. Procedures for starting-up the system and its components
6. Emergency procedures to minimize system upsets and overloading
7. Sampling procedures and process monitoring requirements
8. Routine procedures for operating the system including harvesting schedules
9. Maintenance items and scheduling
10. Trouble-shooting guide for identifying and correcting process or equipment problems.

The O & M of aquaculture treatment systems is characteristically different from that of conventional treatment systems. Lack of experienced personnel for operating APU systems dictates explicit O & M instructions to ensure proper O

& M of the systems. Because the majority of existing and past non-operating aquaculture treatment systems are either experimental in nature or at the pilot-study stage, there is a significant lack of O & M procedures. This is an area which dictates further investigation and research. Better record keeping and dissemination of O & M related data and information is needed to facilitate wider application of aquaculture treatment technologies.

6.1.9 Construction Inspection and Management

In order to maintain aquaculture treatment systems as low-energy, and inexpensive technology alternatives, proper construction supervision and inspection are essential. While too vigorous construction supervision and inspection can increase the cost of aquaculture treatment systems beyond the cost-effective domain. Lack of proper construction supervision and inspection may result in defective systems or systems incapable of performing according to the design and design goals. The best approach to construction supervision, inspection, and management remains to be addressed.

6.2 Summary

Over the last decade much has been learned about design of aquaculture treatment systems. Nevertheless, wider application of the technology and wider acceptance by engineers, regulatory officials, and the public still greatly constrained by various weaknesses in existing technical documentation. These technical constraints to aquaculture technology implementation can be decreased through further documentation with regard to the following:

- Proper procedures for screening, selecting, and adopting candidate aquatic species for the aquaculture treatment project contemplated.
- Better understanding and even quantification of removal mechanisms which occur in an aquaculture treatment system.
- Effects of environmental or climatic factors on these removal mechanisms.
- The threshold concentrations of various pollutants tolerable by various aquatic species.
- The optimal environmental conditions for growing various aquatic species and cost-effective techniques for achieving and maintaining these conditions.

- Better understanding of various wastewaters and levels of pretreatment requirements prior to discharge into an aquatic processing unit (APU).
- Better documented procedures for starting-up, operating, and maintaining an APU and better understanding of APU controllability and strategies for process control.
- Better understanding of the role of biomass harvesting (criteria, timing, and frequency) in an aquaculture treatment system.
- Ability to obtain accurate predictive mathematical models for various APUs by considering dynamic and kinetic nature of APUs.

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Chapter 7

ECONOMICS OF WASTEWATER AQUACULTURE COMPARED TO CONVENTIONAL TREATMENT TECHNOLOGIES

7.0 INTRODUCTION

As has been mentioned, dramatic increases over the last decade in the construction and operating costs of wastewater treatment facilities provide an incentive to seek and apply technologies which keep such costs as low as possible. The one factor which has caused perhaps the greatest increase in operating costs is the use of electrical and fuel energy. Wastewater aquaculture treatment, with its dependence on naturally occurring rather than chemically or mechanically induced pollutant removal can be considered a low-energy technology. Hence, where implementable, aquaculture has the potential for lower operating costs compared to more conventional mechanized technologies while providing tertiary and advanced levels of treatment. As indicated in Table 7.1, the more natural systems such as land treatment and aquaculture have a clear advantage over more mechanized systems on the basis of total annual energy consumption and comparative level of performance.

Tchobanoglous, et al(2) concluded that both land treatment systems and aquaculture treatment systems can offer substantial savings in energy and the amount of resources consumed compared to conventional wastewater treatment systems. Crites also demonstrated that aquaculture can provide a low cost, low energy solution for wastewater treatment.(4) Preliminary calculations by Lee and McKim based on the aquaculture treatment systems at Walt Disney World indicated that the wastewater hyacinth treatment system utilizes only 50 percent of the energy of a comparable activated sludge system for secondary treatment.(5) A separate comparison between total energy use for equivalent performance between an activated sludge process and a constructed wetland process preceded by a facultative pond showed that the energy difference

Table 7.1

TOTAL ANNUAL ENERGY FOR TYPICAL 1 MGD SYSTEM
(ELECTRICAL PLUS FUEL, EXPRESSED AS 1000 KWH/YR)

Treatment system	Effluent quality				Energy 1000 kwh/yr
	BOD	SS	P	N	
Rapid infiltration (facultative pond)	5	1	2	10	150
Slow rate, ridge + furrow (fac. pond)	1	1	0.1	3	181
Overland flow (facultative pond)	5	5	5	3	226
Facultative pond + interm. filter	15	15	-	10	241
Facultative pond + microscreens	30	30	-	15	281
Aerated pond + interm. filter	15	15	-	20	506
Extended aeration + sludge drying	20	20	-	-	683
Extended aeration + interm. filter	15	15	-	-	708
Trickling filter + anaerobic digestion	30	30	-	-	783
RBC + anaerobic digestion	30	30	-	-	794
Trickling filter + gravity filtration	20	10	-	-	805
Trickling filter + N removal + filter	20	10	-	5	838
Activated sludge + anaerobic digestion	20	20	-	-	889
Activated sludge + an. dig. + filter	15	10	-	-	911
Activated sludge + nitrification + filter	15	10	-	-	1,051
Activated sludge + sludge incineration	20	20	-	-	1,440
Activated sludge + AWT	<10	5	<1	<1	3,809
Physical chemical advanced secondary	30	10	1	-	4,464

Source: (1)

between the two processes (activated sludge is higher) increases with increasing flow volume (at least up to 1.0 MGD).(6) Fritz and Helle indicated that the cost of land, length of required force mains, flow, the type of cypress wetland and surroundings are important variables which can have a significant impact on the cost-effectiveness of cypress wetlands aquaculture treatment systems.(7) Further comparisons of land requirements, costs and energy usage for aquaculture and more conventional technologies are summarized in Table 7.2

This study had originally intended to present a variety of case studies of the economics of existing aquaculture facilities. The case studies were to be selected to give a wide representation of geographic location, climatological and hydrogeological characteristics, aquaculture species used, flow volumes, etc. and were to be used for an economic comparison with conventional technologies providing a similar level of treatment performance. As has been noted by other researchers, one of the great difficulties in examining the economics of wastewater aquaculture is the lack of verified design and operating data. In reviewing various operating aquaculture facilities in the course of this study several problems which contribute to the validity of an economic analysis were noted.

For many of the aquaculture facilities, the advantage of the aquaculture technology could not be compared quantitatively to conditions which existed prior to aquaculture implementation. In other cases aquaculture facilities have been retrofitted and design or construction quality may not be comparable to a newly designed system. For example, the water hyacinth pond at the Hornsby Bend sludge plant in Austin, Texas ranges from a few inches in depth near the inlet to more than eight feet at the outlet, and is subject to short circuiting due to its physical characteristics. Better performance would be expected if such problems could be remedied, and it would be unfair to compare this system to an ideal conventional treatment system without such problems.

The majority of aquaculture systems were, or are, research projects, which typically have different cost associated with them than do non-research wastewater treatment systems. For example, construction, operating and monitoring is often provided by students and such situations are not comparable to faciilties which have been designed, bid, constructed and operated like

Table 7.2

EXAMPLES OF TYPICAL LAND REQUIREMENTS, TOTAL CONSTRUCTION COSTS, LABOR REQUIREMENTS, PARTS & SUPPLY COSTS, AND TOTAL ENERGY REQUIREMENTS FOR NATURAL TREATMENT SYSTEMS, ACTIVATED SLUDGE AND TRICKLING FILTER SYSTEMS

Treatment[a] System	Land req'd, acres Plant size, mgd			Total Const. Cost,[b] $x10^{-6} Plant size, mgd			Labor req'd, p·h/yr Plant size, mgd			Parts & Supplies, $/yr x 10^{-2} Plant size, mgd			Total Energy,[d] Btu/yr x 1 Plant size, mgd		
	0.1	0.5	1.0	0.1	0.5	1.0	0.1	0.5	1.0	0.1	0.5	1.0	0.1	0.5	1.0
Conventional Systems[f]															
Activated Sludge + Cl$^-$	1.0	2.5	4.0	0.710	1.234	1.600	1600	3600	5500	80	120	160	1852	5033	7480
High Rate (Rx) Trickling Filter + Cl$^-$	1.5	3.0	5.0	0.732	1.276	1.700	1200	2800	4200	60	100	140	1641	3659	6044
Land Treatment Systems[g]															
Primary + Overland Flow + Cl$^-$	6.5	30.8	61.5	0.401	0.662	1.050	1500	3150	4200	65	95	130	1112	2266	3795
Primary + Rapid Infiltration	2.5	10.8	21.5	0.311	0.472	0.790	1500	2950	4000	55	90	120	953	1896	3124
Primary + Slow Rate (ss)	16.5	80.8	161.5	0.481	0.902	1.500	2000	3150	4200	65	95	130	1326	3136	5405
Primary + Slow Rate (r & f)	16.5	80.8	161.5	0.421	0.712	1.130	2000	3150	4200	65	95	130	976	2126	3425
Fac. Pond + Over. Flow	11.0	45.0	90.0	0.530	1.225	1.950	2000	4400	5700	90	135	180	1223	2352	3765
Fac. Pond + Rapid Infl.	7.0	25.0	50.0	0.444	1.035	1.690	2000	4200	5500	80	130	170	1106	2171	3470
Fac. Pond + Slow Rate (ss)	21.0	95.0	163.0	0.610	1.465	2.400	2500	4400	5700	90	135	180	1305	2788	4770
Fac. Pond + Slow Rate (r+f)	21.0	95.0	163.0	0.550	1.275	2.030	2500	4400	5700	90	135	180	1132	2032	3320
Aquatic Treatment Systems[h]															
Primary + Artif. Wetland + Cl$^-$	4.5	20.8	41.5	0.361	0.552	0.900	1000	2250	3000	35	45	60	1003	2038	3470
Primary + Water Hyacinths + Cl$^-$	2.5	10.8	21.5	0.331	0.522	0.830	2000	2750	4000	35	55	80	1020	2309	3050
Fac. Pond + Artif. Wetland	9.0	35.0	70.0	0.490	1.115	1.600	1500	3500	4500	60	85	110	1114	2154	3452
Fac. Pond + Water Hyacinths	7.0	25.0	50.0	0.460	1.085	1.730	2500	4000	5500	60	95	130	1132	2425	3921

[a] Adapted from Tchobanoglous, et al., 1979
[b] land cost not included
[c] p·h/yr = person hours per year
[d] includes both primary energy (electricity and fuel) and secondary energy (plant construction, chemicals, parts & supplies, etc.)
[e] assumes influent to all systems is domestic wastewater with BOD$_5$ & SS = 220 mg/l
[f] effluent expected to achieve BOD$_5$ & SS = 30 mg/l
[g] effluent expected to acheive BOD$_5$ & SS = 10 mg/l, nurtient removal will vary with mode of operation
[h] effluent expected to achieve BOD$_5$ & SS = 30 mg/l, nurtient removal will vary with mode of operation
ss solid set irrigation system
r&f ridge & furrow irrigation system

Source: (3)

non-research facilities. Additionally, certain regulatory requirements for components such as liners and coverings may have been relaxed for research projects. Additional or special equipment may also have been provided for research projects which might otherwise not be used in a conventional project. For example, the hyacinth basins at the Walt Disney World research facility were constructed with concrete and provided with additional piping and valving for varying the operating modes for research purposes.

Wastewater aquaculture facilities in general are land-intensive, but in the majority of aquaculture facilities surveyed, the required land was already available at no additional cost. This situation would tend to give an unfair cost comparison with conventional processes which are less land intensive. For example, the Coral Springs aquaculture facility was constructed on available land with no additional cost for the land. Since land in this area assumedly has a high cost due to its prime location, aquaculture technology may not have been cost-effective if the land had been purchased.

Finally, cost information for privately financed industrial aquaculture facilities could not be obtained due to a perceived reluctance to share such information with competitors.

7.1 Case Studies

Due to the limited amount of meaningful economic data on existing aquaculture facilities for the reasons listed above, it was not possible to present ten existing case studies, nor to use selection criteria based on location, flow, etc. as originally desired. Eight total case studies, four based on existing aquaculture facilities, three that deal with planned future aquaculture facilities, and one hypothetical case study have been presented to provide further insight into the economics of various aquaculture facilities.

Where appropriate, conventional processes capable of achieving effluent qualities similar to aquaculture processes were compared with the existing facilities. Cost data for the comparable conventional processes was derived from the U.S. EPA Innovative and Alternative Technology Assessment Manual(8) or from best engineering judgement when data was not available. Economic comparisons were based on an evaluation of present worth for the first year of the system operation in accordance with EPA cost-effectiveness analysis guidelines.(9)

A hypothetical situation case study based on critical, fixed, site-specific conditions and regulatory guidelines is presented to incorporate certain factors, such as land costs, which were not included in the other case studies offered. Because land requirements are usually greater for aquaculture technology, it was felt that a case study comparing alternatives with land cost included must be presented to show the effect of land purchase on cost-effectiveness. Design and cost estimates for the hypothetical case study were generated as if for a Step 1 Sewerage Facilities Plan. The hypothetical case involves the upgrading of effluent from a stabilization pond located in Texas. The State of Texas is the only state with design guidelines(10) for aquaculture technology.

The following case studies will be presented:

- National Space Technological laboratories, Bay St. Louis MS (existing)
- Houghton Lake, MI (existing)
- Coral Springs, FL (existing)
- Lake Helen, FL (existing)
- Gilbert, AZ (future)
- Shreveport, LA (future)
- Austin, TX (future)
- Hypothetical Case Study, Texas

Tables 7.3 through 7.9 present summary descriptions and the findings of all but the hypothetical case. A comment is included for each case to summarize economic findings of the cost comparisons.

7.1.1 Hypothetical Case Study

For the hypothetical situation it has been assumed that the State of Texas is requiring a POTW to be upgraded in terms of suspended solids removal. A suspended solids limit of 30 mg/l has been proposed. The existing system, designed under Texas Department of Health Guidelines(10) consists of a 5.6 acre facultative pond receiving raw wastewater, followed by a 5.6 acre initial stabilization pond and a 6.3 acre final stabilization pond. A 100 foot fenced buffer area surrounds the facility.

Table 7.3

COST COMPARISON BETWEEN AQUACULTURE AND CONVENTIONAL TREATMENT ALTERNATIVE

Case Study No. 1

Location: National Space Technology Laboratories - Bay St. Louis, Mississippi

Description: Upgrade existing 2 ha. (4.9 ac.) domestic wastewater lagoon No. 1 to meet effluent suspended solids limitation.

Operating Conditions

Average Flow : 475 m^3/d (0.125 mgd)
Surface Area : 2.0 ha (4.9 ac.)
Average Depth : 1.2 M (4.0 ft.)
Detention Time: 54 days
BOD_5 Loading : 26 kg/ha-day (23.1 lbs/ac-day)

	Mean Effluent Quality (mq/1)		
	Before	After	Permit
BOD_5	17	5	30
TSS	49	10	30

Facilities Requirement :

Aquaculture	Conventional Alternative
• Add hyacinths to existing lagoon to reduce suspended solids	• Dual media filter

Cost Item *	Aquaculture ($)	Conventional Alternative ($)
Capital Cost	1,200	80,000
O, M & R Cost	960	6,800
Revenues	0	0
Present Worth	12,100	157,500

* 1976 Cost; i = 6-1/8%; Salvage = 0

Comment: Addition of water hyacinths to lagoon upgraded performance to more than satisfy effluent requirement. Capital costs were minimal due to existing lagoon. Harvesting costs have been minimal. Aquaculture was significantly more cost effective due to low capital cost and energy usage. Note that hyacinth facility is limited to warm climate area.

References:(8, 11, 12, 13)

Table 7.4

COST COMPARISON BETWEEN AQUACULTURE AND CONVENTIONAL TREATMENT ALTERNATIVE

Cast Study No. 2

Location: Houghton Lake Sewer Authority Wastewater Treatment Plant - Houghton Lake, Michigan

Description: Upgrade existing aerated lagoon effluent by pumping to natural wetland to meet suspended solids and total phosphorous limitation (domestic wastewater)

Operating Conditions

Seasonal Wetland Discharge: 3785 m^3/d-5678 M^3/d
(1.0 MGD-1.5 MGD)

	Mean Effluent Quality (mg/1)		
	Before^A	After	Permit
TSS	18	--^{B}	10
TP	4	.5	.5^C

A - Estimated
B - Not determined because of detritus
C - Total dissolved phosphorus

Facilities Requirement:

Aquaculture	Conventional Alternative
- Holding pond modification - Dechlorination Pond - Pond wetland transmission - Irrigation header system - Monitoring equipment	- Chemical feed unit - Dual media filtration

Cost Item*	Aquaculture ($)	Conventional Alternative ($)
Capital Cost	400,000	543,000
O, M & R Cost	36,000	68,500
Revenues	0	0
Present Worth	794,200	1,293,075

* 1978 cost; i = 6-5/8%; salvage = 0

Comment: An example of a natural system is an area subject to sub-freezing winter weather. The most notable cost difference between these two technologies is the O, M, and R cost due to more labor, energy and chemicals for the conventional alternative. The facility meets effluent discharge limits and no significant advers environmental impacts have been reported. The aquaculture technology is cost effective.

Table 7.5

COST COMPARISON BETWEEN AQUACULTURE AND CONVENTIONAL TECHNOLOGY
Case Study No. 3

Location: Coral Springs Improvement District Wastewater Treatment Plant - Coral Springs, Florida

Description: Upgrade existing activated sludge process effluent by hyacinth system to advanced wastewater standards (domestic wastewater)

Operating Conditions

Average Flow : 378.5 m^3/d (.1 MGD)
Total Surface Area: 0.5 ha (1.25 ac)
Detention Time : 6.0 days
Water Depth : 0.38 m (1.25 ft)

Mean Effluent Quality (mg/l)			
	Before^A	After^A	Permit
BOD_5	20	5	5
TSS	25	3	5
TN	9	1-2.5	3
TP	8	8	1

A - Estimated

Facilities Requirement:

Aquaculture	Conventional Alternative
- Five hyacinth culture ponds in series	- Nitrification (seperate stage) process - Denitrification (fine media) process - Dual media filtration

Cost Item*	Aquaculture ($)	Conventional Alternative ($)
Capital Cost	66,000	513,000
O, M, & R Cost	13,500	61,000
Revenues	0	0
Present Worth	213,825	1,180,950

* 1978 cost; i = 6-5/8%; salvage = 0

Comment: The hyacinth system alone does not meet the total phosphorous discharge standard, therefore this cost comparison deleted a unit process for phosphorus removal for the conventional alternative. Capital and O M & R cost are extremely high for mechanical treatment processes. Since a phosphorus removal unit proces would be required for each of the comparable systems, it can be inferred that the aquaculture technology plus phosphorus removal process together, would be the most cost effective. Note that land was available at no cost.

Reference: (8, 16, 17)

Table 7.6

COST COMPARISONS BETWEEN AQUACULTURE AND CONVENTIONAL TREATMENT ALTERNATIVES

Case Study No. 4

Location: Hyacinth demonstration project - Lake Helen, Florida

Description: Upgrade primary effluent like (synthetic wastewater) by hyacinth system (including methane recovery) to meet stringent design effluent standards.

Operating Conditions

Average Flow: 26.4 m^3/d (.007 MGD)
4 Lagoons : 0.17 ha (0.41 ac)
Mean Depth : (1.1 m) 3.5 ft

Mean Effluent Quality (mg/l)			
	Before	After[A]	Permit[B]
BOD_5	65	2	--
TSS	40	2	--
TN	25	2	--
TP	7	0.2	--
A - Estimated		B - No Limitations	

Facility Requirement:

Aquaculture	Conventional Alternative
• 4 calcium bentonite lined hyacinth lagoons in series • Methane recovery process	• Not Determined

Cost Item *		Aquaculture($)	Conventional Alternative ($)
Capital Cost:	4 Lagoons Cost	$24,500	Not Determined
	Yard Piping	5,000	
	Storage Building	15,000	
	Fencing	2,500	
	Digestor Tank w/Insulation	4,000	
	Fabrication Costs	1,300	
	Compressor for Methane	2,500	
	pH Controller	5,000	
	Temperature Controller	500	
	Pressure Controls	500	
	Storage Tank (250 gallon)	1,000	
	Concrete Slab	300	
	Flow Metering	1,200	

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	Level Meters	1,200
	Harvesting Equipment	5,000
	Pumps	1,500
	Seeding and Mulching	600
	Spare Parts & Misc.	500
	Sub Total	$77,100
	Land (1.5 ac x 3000)	4,500
	TOTAL	$81,600
O, M & R Cost:	Electricity @ $0.08/kwh	$ 1,500
	Labor 8 hr/wk @ $10.00/hr	4,160
	Fuel 10 gal/wk @ $1.50 gal	780
	Laboratory @ $25/wk	1,300
	Administrative	1,000
	Chemicals	400
	Miscellaneous	400
	TOTAL	$ 9,540
Revenues:	Methane value recovered estimated 100 MBTU @$10/MBTU	1,000
Present Worth:	Not Determined	
* 1981		

Summary: Performance data for this privately funded demonstration project are not available at this time because the facility recently started operation. However, these costs have been included because the capital costs were the actual costs for the facility. The estimated O, M, and R costs are also provided. Note that this facility includes methane generation.

Reference: (18)

Table 7.7

COST COMPARISON BETWEEN AQUACULTURE AND CONVENTIONAL TREATMENT ALTERNATIVES

Case Study No. 5

Location: North Study Area - Gilbert, Arizona

Description: A solar aquaculture process has been proposed to treat raw screened domestic wastewater.

Operating Conditions

Projected Flow: 6435 m^3/d (1.7 MGD)

	Mean Water Quality (mg/l)	
	Projected Influent	Projected Effluent
BOD_5	200	10
TSS	275	10

Facilities Requirement :

Aquaculture	Conventional Alternative
• Lift Station	• Lift Station
• Static Screen	• Static Screens
• Faculative Cell	• RBC
• Aerobic Cell	• Secondary Clarification
• Rotoscreen	• Chlorination
• Rapid Sand Filter	• Digestion
• Chlorination	• Composting
• Composting	

Cost Item*	Aquaculture ($)	Conventional Alternative ($)
Capital Cost (annual)	420,000	434,000
O, M & R Cost (annual	95,000	163,000
Revenues	0	0
Total Annual Cost	515,000	597,000
i = 6-7/8%		

Comment: The 201 facilities plan concluded that a solar aquaculture facility was more cost effective than an RBC process. Note that land is available at no cost.

Reference: (19, 20)

Table 7.8

COST COMPARISON BETWEEN AQUACULTURE AND CONVENTIONAL TREATMENT ALTERNATIVE

Case Study No. 6

Location: North Regional Wastewater Treatment Plant - Shreveport, Louisiana

Description: Aerated lagoon followed by a three celled hyacinth pond proposed to treat raw domestic wastewaters.

Operation Conditions

Projected Flow : 26,500 m^3/d (7.0 MGD)
Surface Area : 26.6 ha (66 ac)
Depth : 1.2 m (4.0 ft)
Detention Time : 10 days
Average BOD_5 Loading: (85.1 kg/ha-da) (76 lb/ac-da)

Mean Water Quality (mg/l)		
	Projected Lagoon Effluent	Permit
BOD_5	86	30
TSS	--A	30

A - Not Available

Facilities Requirement:

Aquaculture	Conventional Alternative
• Aerated lagoon followed by a 3 celled hyacinth pond • Chlorination	• Race track oxidation ditch system • Chlorination

Cost Item*	Aquaculture ($)	Conventional Alternative ($)
Capital Cost	5,322,000	5,903,000
O & M Cost	223,000	236,000
Present Worth	7,890,000	8,342,000

* i - Not Available

Comment: The 201 facilities plan concluded that an aerated lagoon followed by a three celled hyacinth pond was more cost effective than a race track oxidation ditch system.

Reference: (21)

Table 7.9

COST COMPARISON BETWEEN AQUACULTURE AND CONVENTIONAL TREATMENT ALTERNATIVES

Case Study No. 7

Location: Hornsby Bend Sludge Treatment Plant - Austin, Texas

Description: Proposed upgrading and covering of existing hyacinth pond for the partial treatment of sludge from three area wastewater treatment plants.

Operating Conditions

None Available

Mean Water Quality Data

None Available

Facilities Requirement:

Aquaculture	Conventional Alternative
- Modify existing hyacinth pond (earthwork) - Greenhouse - Disposal Equipment	- Pump supernatent liquor to Onion Creek Plant (plant must be sized larger than aquaculture alternative)

Cost Item*	Aquaculture ($)	Conventional Alternative($)
Capital Cost	893,875	1,232,452
O, M, & R	Not Available	Not Available
Present Worth	Not Available	Not Available
* i - Not Available		

Comment: The 201 facilities plan concluded that upgrading and covering the existing hyacinth pond was more cost effective than pumping digester supernatent at the Hornsby facility back to the enlarged Onion Creek Wastewater Treatment Plant. Example of aquaculture for sludge management.

Reference: (22)

To upgrade the stabilization pond effluent to meet effluent limits of 30 mg/l BOD and suspended solids the following alternatives were considered:

- Water Hyacinth Aquaculture System
- Intermittent Sand Filtration System
- Microscreen or Rapid Sand Filter

The following critical site specific variables were assumed:

- Design Flow: 0.5 MGD
- BOD_5 raw wastewater: 200 mg/l
- Existing final stabilization pond effluent quality: 30 mg/l BOD, 90 mg/l SS
- Existing system is already at maximum organic loading: 165 kg/ha/d (150lbs/ac/d) for facultative lagoon, 38.5 kg/ha/d (35 lbs/ac/d) for final stabilization pond
- No chlorination requirement for final effluent
- 30.5 m (100 ft) buffer area fencing requirement
- Additional land must be purchased at $1600/ha ($4,000/ac)
- Site layout provides gravity flow from final stabilization pond
- Clay soils
- Solids handling not desired
- Operators salary including benefits: $18/hr
- Electrical cost $0.10/kw hr
- Interest rate 7-5/8%
- Engineering administration contingency: 25%

Three different options were considered for the water hyacinth alternative due to variable Texas regulatory requirements which, depending on location, may require either a lagoon cover or a liner. These options were:

- No liner or cover requirement
- Liner requirement, no cover requirement
- Cover requirement, no liner requirement. (A system with a liner and cover requirement was not considered.)

The hyacinth alternative was formulated from available design criteria published by the Texas Board of Health(10) and best engineering judgement. The following criteria was used as the basis of the water hyacinth facility alternative:

- Hydraulic loading: .08 MG/ha/d (0.2 MG/ac/d)
- Maximum basin size: 0.40 ha (1.0 ac)
- Max basin width: 9.1 m (30.0 ft)
- Water depth: 0.61 m (2.0 ft)
- One additional basin required for emergency back-up

The resulting system consisted of four hyacinth basins in series, each with a surface area of 368 m x 9 m (1210' x 30'). An additional 4.6 ha (11.3 ac) of land is required to be purchased. Minimal daily operator attention (1 hr/d) is assumed. The hyacinths are to be harvested once per year with a rented front loader and dried on-site. No further by-product utilization is assumed.

The estimated cost of the hyacinth alternative is presented in Table 7.10. As shown, the liner requirement would add approximately $66,000 to the capital cost. The cover requirement would add an estimated $1,187,500 to the capital cost and would need to be replaced in 10 years.

Intermittent Sand Filter Alternative - The design for the intermittent sand filter alternative was based on available design criteria(8) and best engineering judgement. The following criteria was used as the basis of this alternative:

- Hydraulic loading: 0.2 MG/ha/d (0.5 MG/ac/d)
- Filter drying time: 2 days
- Operating depth: 1.07 m (3.5 ft)

The resulting system would consist of 3 filter beds, each with a surface area of 110 m x 36.6 m (360' x 120'). Additional land (3.03 ha (7.5 ac) purchase is required to accommodate the filter beds. The daily estimated operator attention is assumed minimal at 1 hr/d. The top 2 inches of sand are to be removed, and replaced every 45 days with a rented tractor.

Table 7.10 shows the estimated cost of this alternative compared to the aquaculture alternative.

Microscreen or Rapid Sand Filter Alternative - From a cursory design analysis the microscreen or rapid sand filter alternatives were determined to have roughly the same cost and are therefore presented together. The following criteria was used as the basis for this alternative:

- Hydraulic loading (microscreen): 1.02 l/m^2-s (1.5 gpm/ft^2) net effective submerged area
- Hydraulic loading (rapid sand filter): 1.36 l/m^2-s (1.5 gpm/ft^2) surface area
- 2-day holding tank required for emergency by-pass cover requirement.
- Cover required.

Table 7.10

ESTIMATED COSTS FOR SELECTED ALTERNATIVES: HYPOTHETICAL CASE STUDY

Costs	Alternative				
	Hyacinth No Liner No Cover	Hyacinth Liner No Cover	Hyacinth No Liner Cover	Intermittent Sand Filter	Microscreenor Rapid Sand Filter
Capital*	123,000	189,000	1,310,000	434,500	290,000
Land	45,500	45,500	45,500	30,000	0
Total	168,500	234,500	1,355,500	464,500	290,000
O, M, and R					
Labor	12,000	12,000	12,000	14,500	10,000
Energy	0	0	0	0	4,500
Chemicals & Materials	0	0	0	9,500	500
Replacement	3,000	3,000	3,000	8,500	6,000
Total	15,000	15,000	15,000	32,000	21,000
Present Worth**	301,500	367,500	1,488,500	781,000	502,500

* Includes 25% for Engineering, Administrative, Contingencies
** i = 7-5/8%; Salvage for land only.

The resulting system consisted either of a 3.0 m (10 ft) diameter by 4.9 m (16 ft) microscreen or a 1.8 m by 11.0 m (6' x 36') rapid sand filter (automatic back wash). It was assumed that the unit process could be placed on existing owned land and additional land was not necessary. Because the existing plant is being loaded to the maximum BOD_5 level, the facultative lagoon surface must be enlarged by 0.52 ha (1.3 ac). The microscreen or rapid sand filter are more mechanically complex than the other two alternatives, so additional daily operation attention was considered.

Table 7.10 compares the estimated costs of this alternative with the other alternatives in this hypothetical situation. The U.S. EPA guidelines for determining cost-effectiveness were followed.(9)

From this hypothetical design process the following variables were observed to have an influence on the cost of the hyacinth alternative and therefore also influence the ranking of alternatives.

- Quantity of flow
- Design influent water quality parameters
- Design effluent water quality parameters
- Land cost
- Land availability
- Climate, geology, topography, soil type
- Electrical cost
- Desired solids handling method, growth rate
- Skill and salary of available operator
- Requirements of governing regulatory board
    - liner
    - cover
    - buffer zone
    - emergency back-up uints
    - others
- Current loading on existing unit processes
- Salvage value
- Interest rate, engineering, administrative, contingencies
- Revenues from by-product,if any.

As can be seen in Table 7.10, four hyacinth lagoons in series with no liner or cover would provide the most cost-effective alternative in terms of present worth, even though there is a requirement for purchase of additional land. While this situation is extremely site specific, this case study presents the variables that can influence the cost of APU's and should be of value to planners.

The next most cost-effective alternative would be lined hyacinth lagoons. As shown in the comparison, the high cost of covering hyacinth lagoons to achieve continual year-round growth can have an adverse effect on cost-effectiveness. The intermittent sand filter alternative has comparatively higher costs due to piping and other materials costs. Operating costs are comparatively high due to sand replacement cost and greater labor involvement with removing, and replacing filter media.

The rapid sand filter or microscreen alternative is less cost-effective in terms of present worth than the uncovered hyacinth alternative regardless of the additional land cost for the hyacinth alternative. This is due to higher equipment cost and the solids handling problem which required enlargement of the existing facultative lagoon. Labor costs are less for this alternative compared to hyacinth aquaculture, but energy and replacement costs would be higher.

It must be noted from this hypothetical example that, while aquaculture can be cost-effective, site specific conditions may cause more conventional technologies to be more favorable. It can also be inferred that aquaculture probably has its greatest application in areas where land is available at low cost and where regulatory or physiographic limitations do not force the use of components like lagoon liners, covers or other items which can significantly affect costs. Finally, it is apparent that if a by-product can be harvested and marketed to produce revenues, cost-effectiveness can be enhanced.

7.2 Summary

Although meaningful economic comparisons between wastewater aquaculture technologies and conventional technologies are difficult to derive at this stage of aquaculture development, case studies for certain existing facilities indicate that aquaculture technology can be a cost-effective, low-energy alternative which provides a satisfactory quality effluent. Recent wastewater facility plans are at least considering wastewater aquaculture, and some have concluded that aquaculture technology is cost-effective compared to conventional alternatives. Economic comparisons between wastewater alternatives must be based on site specific variables for each contemplated application.

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CHAPTER 8

BY-PRODUCTS DERIVED FROM WASTEWATER AQUACULTURE

8.0 GENERAL

A significant deterrent to the aquaculture industry in the United States is in the harvesting, processing and marketing of cultured species from clean waters and in obtaining consumer acceptability for those products. Development of a new industry often progresses from the elimination of technical problems in production to the development of markets, once a marketable product has been achieved. In many cases clean water aquaculture in the United States is between these stages, where a product is finally available in sufficient quantities for market, but the producer lacks sufficient manpower, capital, time and market information to successfully develop the available markets. Without successful marketing procedures, it is virtually impossible to make consumers either aware of or receptive to new products.

Considering that wastewater aquaculture is a limited segment of the aquaculture industry, the problems encountered in the processing and marketing of the products and in obtaining consumer acceptance of the marketed product are severely compounded. The greatest constraints reside in the potential contamination of the waste-grown aquaculture product by disease-causing organisms or toxic and/or carcinogenic substances, and a generally negative psychological response by humans toward any items derived from wastewater.(9) Thus, added to the operational barriers of the aquaculture industry as a whole, are the legal and emotional barriers which limit the acceptability of food and fiber products derived from wastewater aquaculture.

8.1 Potential Uses of Aquaculture Products Derived from Wastewater

At the present time, the primary concern of wastewater aquaculture in the United States is the production of clean water. However, by their very nature, aquaculture systems create secondary products other than clean water, namely the aquatic species which are cultured. The secondary products can be viewed in two ways: either simply as a by-product of the treatment process which must be disposed of, much as sludge in conventional treatment processes, or as a useful co-product of the treatment system, which has some commercial or social value. Examples of both can be found in current wastewater aquaculture technology. The domestic wastewater treatment facility at Benton, Arkansas cultures silver and bighead carp in combined aquaculture-based treatment lagoons. Harvested fish from this facility are disposed of by burial, even though analysis of the processed fish flesh has indicated that contamination above the U.S. Food and Drug Administration rejection levels does not exist(1).

Other wastewater aquaculture systems have experimented with by-product utilization, primarily using harvested vegetation as animal feed supplements,(34) or after composting, as a soil amendment. As an example, the demonstration wastewater hyacinth system at Walt Disney World, Florida currently composts harvested water hyacinths by the static pile method and allows them to decompose without further turning or processing. The stabilized end-product is transported to an ornamental tree farm where it is applied as a soil amendment and supplemental nutrient source(2).

Many different uses for the by-products of wastewater aquaculture systems have been identified. Each use encounters a variety of different constraints; some of them obviously being more sensitive than others.

8.2 Food for Direct Human Consumption

There currently exists a potential for the production, marketing, and consumption of aquaculturally grown products in the United States. This is evident in the fact that U.S. consumption of freshwater and seafood products exceeds the rate of production(3) and large quantities are imported from foreign countries each year. Foreign import dependence could be decreased if domestic fish and shellfish production could be increased through utilization and recycling of the nutrients found in many biological wastewaters.

Suffern et al (1981)(35) reports that current estimates of production from the phytoplankton-bivalve mollusk food chain system developed at Woods Hole indicate that a wastewater aquaculture system treating the domestic waste of a town of 50,000 could potentially produce an annual crop of over 900 tons of oysters, a valuable seafood crop.

The largest single operating expense to fish culturists is the cost of feed for high density culture.(4) Accordingly, any acceptable and inexpensive feed supplement becomes economically attractive. Hephner and Schroeder(5) demonstrated that organic wastes applied to fish rearing ponds stimulated an increase in natural food sources (zooplankton and chironomids) available to fish. Thus, the incentive to use wastewaters in fish culture is clear. The most significant deterrent to this practice is the concern that pathogenic micro-organisms and other potentially harmful wastewater constituents which coexist with the beneficial nutrients may be bio-accumulated and concentrated in the fish and passed on to consumers. Carpenter, et al(6) investigated microbial pathogens in sewage and sewage-grown fish in a six-cell lagoon system in Quail Creek, Oklahoma. Three pathogens were identified in the raw sewage influent but none were found beyond the second cell (which did not contain fish), and pathogens could not be isolated in any of the 179 fish sampled.

Suffern et al.,(35) studied bioaccumulation and biomagnification of heavy metals in raw wastewaters at Oak Ridge National Laboratory in a two-pond food chain polyculture wastewater aquaculture system where tilapia were suspended in cage culture. Those metals studied; Cd, Cr, Cu, Ni, Pb and Zn tended to decrease in concentration at higher trophic levels. They also found the major reservoir of heavy metals to be the bottom sediments or sludge in the systems. Suffern suggests that the tilapia cultured may be increasing in weight and size faster than they can accumulate metals, thus diluting the heavy metal concentrations in the fish flesh. In addition, the high concentrations of organic complexes present in the water may also explain the low metal accumulation rates in higher trophic levels.

The direct use of wastewaters in ponds with active fish culture is perhaps the most sensitive practice in terms of contaminants being taken up by harvested organisms. The further the wastes are separated from the product, the less sensitive to contamination the product should become. The concept of polyculture may well suit this separation requirement. Polyculture systems include the culture of several organisms in a food chain; one organism being cultured as a food source for another, and that organism cultured and harvested for another, and so on, until the final product is obtained. This idea, as diagrammed in Figure 8.1, has been the subject of research at Woods Hole Oceanographic Institute(7) in marine (mariculture) food chains and has proven a promising, but more costly alternative.

A somewhat analogous concept is that of raising bait minnows in wastewater facilities. The minnows would be a lucrative product that would never be directly consumed by humans.

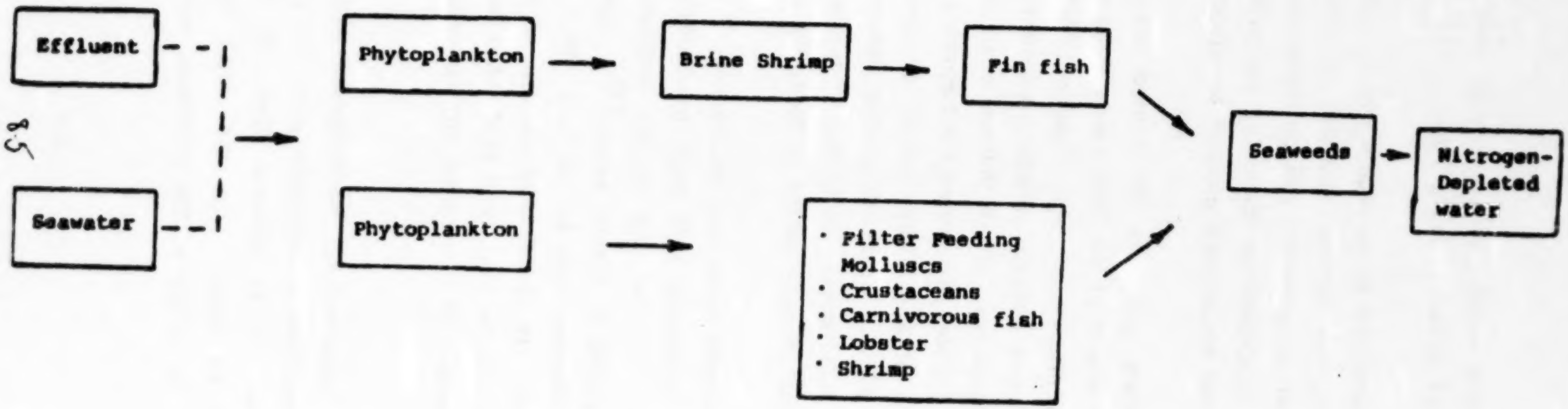
Another approach to obtaining valuable and acceptable fish by-products from wastewater aquaculture would be to provide for only a portion of the life cycle of fish in the wastewater aquaculture facility. Fish would be reared for only a portion of their life cycle in a wastewater aquaculture environment and then transferred either to a clean-water aquaculture facility or natural clean-water environment for a period of time which allows both significant growth and depuration. Depuration would greatly reduce the potential risks to human consumption and there would also be a potential to improve the quality of the fish product through controlled feeding and diet. In Michigan and Wisconsin there have been efforts to rear fingerling game fish, like the muskellunge, in wastewater facilities, for eventual release. While sport fish rearing in public or industrial wastewater facilities might not produce direct monetary returns, donation of sport fish for stocking public waters would result in certain public relations benefits and would free state facilities from rearing of fingerling sport fishes.(36)

Additionally, rearing of Gambusia or mosquito fish in wastewater aquaculture facilities may be a socially and commercially valuable product in regions where mosquito control is important. Gambusia can be sold to mosquito control districts for stocking in mosquito habitat.(36)

The harvesting and processing of plant biomass from a wastewater aquaculture system can lead to indirect by-product utilization for human consumption.

Figure 8.1

FOOD CHAIN POLYCULTURE(7)


Effluent
Seawater
Phytoplankton
Brine Shrimp
Fin fish
Phytoplankton
· Filter Feeding Molluscs
· Crustaceans
· Carnivorous fish
· Lobster
· Shrimp
Seaweeds
Nitrogen-Depleted water

Indirect uses encompass waste-grown plants as feed for cattle or poultry, which are ultimately used for human consumption.

If the safety of aquaculture by-products grown in wastewater supplied systems can be assured then, the further question of consumer acceptability must be addressed. Consumer acceptability can be influenced to a significant degree by imposed regulatory constraints in marketing the products, governmental support of product purity, and educational support in advertising.

Wastewater aquaculture products for human consumption face serious legal obstacles from enforcement of the 1938 Food, Drug and Cosmetic Act(8) which is concerned with "adulteration" and "misbranding". Huguenin and Little(9) addressed the legal and political problems encountered for waste-grown aquatic foods under this regulation. They indicate that waste-grown aquatic foods can be easily condemned under the broadly interpreted phrase in the law: "consists in whole or in part of any filthy, putrid or decomposed substances", or "is otherwise unfit for food". In addition, they discuss the inconsistencies between regulations over substances occurring "naturally" in foods, and those intentionally or unintentionally added to foods by man.

With respect to naturally occurring substances, it is important to emphasize that researchers have suggested that high productivity in estuarine environments could, at least in part, be due to the increased nutrients discharged from sewage treatment plants in coastal areas.(10) Aquatic foods derived from these areas would be condemned only in the case where they were demonstrated to be dangerous to health. In the case of wastewater aquaculture food products, the same substances would be perceived as "added intentionally" by man, and thus the products condemned if there were any concern over health hazards(9).

With respect to "misbranding" waste-grown aquatic foods, if the wastewater aquaculturist is required to explicitly label the products as being derived from wastewater sources, it is obvious that the negative impact on consumer acceptability will be great. On the other hand, if concerned regulatory agencies endorse the safety of the products, and participate in the educational advertising which supports the proven quality; it may be more acceptable to the consumer by reducing the psychological barriers.

8.3 Soil Amendments, Fertilizers and Compost

The use of wastewater aquaculture by-products as soil amendments, fertilizers and composts represents perhaps the least sensitive alternative in terms of public health and consumer acceptability. However, it also represents an alternative which could provide the least economic return. Bruhn and Koegel(11) studied the utilization of harvested Eurasian watermilfoil and filamentous algae as soil conditioners and fertilizer and found that the economic return of the products would cover only 10 percent of the harvesting costs. When assessing the market value of water hyacinths as compost, Robinson et al,(12) found that the compost value of hyacinths was comparable to peat moss compost, but that a defined market for composts per se, was not identifiable. Conversely, Bagnall et al.,(13) found that water hyacinth compost could be produced at a cost of \$3 per ton, and sold for \$46/ton to "a readily developable market of nurserymen and home gardners".

Currently, the discussion of wastewater aquaculture by-products utilization for composts, fertilizers and soil amendments has centered around the use of aquatic vegetation. Much research has been devoted to the water hyacinth and its nitrogen, phosphorus and potassium content, its water retention value and processing needs for ease of handling and transport. Research in these areas utilizing other wastewater aquaculture plant species is necessary, as the economical use of water hyacinths in these systems is limited to geographic locations where climate is suitable.

The fertilizer value of aquatic plant species is highly variable; being influenced by processing methods, stage of growth, nutrient availability in the water body in which it is grown, to mention only a few. Robinson et al.,(12) found water hyacinths to have an average primary nutrient content of 1.61 percent N, 0.71 percent P_2O_5, and 4.59 percent K_2O, which compared poorly to the concentration of the same nutrients in commercially available mineral fertilizers. However, an important characteristic to consider when comparing processed water hyacinth with mineral fertilizers, is that water hyacinths represent an organic fertilizer source, which releases nuturients to the soil over a period of time.(14) Mineral fertilizers, on the other hand, are applied in the available form for plant uptake, a highly soluble form which is extremely vulnerable to loss from system due to leaching.

Aquatic vegetation is not the only by-product of wastewater aquaculture systems with potential fertilizer value. Processed liquified fish emulsions are currently being used as organic fertilizers on croplands.(15) As organic farming practices increase, and petroleum based mineral fertilizers escalate in price, the use of natural fertilizers such as this is expected to increase. A local organic fertilizer market has already been delineated for the expected yearly harvest of fish from a proposed finfish wastewater aquaculture system for the Town of New Castle, Virginia.(16) The tentative plan involves an enzymatic anaerobic liquid digestion process for the harvested mosquito fish (Gambusia) and fathead minnows to obtain a fish-emulsion fertilizer product valued at 50¢/gal.(15) The marketing of this product will involve emphasis of its benefits as a replacement liquid nitrogen, lower comparative cost, and benefit to the soil, because liquid nitrogen depletes the organic content of soils, while the fish emulsion would actually improve organic content.

While the fertilizer value of aquatic plants and animals is admittedly less than conventional mineral fertilizers, several other benefits are associated with the use of organic fertilizers derived from wastewater sources. Harvested vegetation and organisms are by-products of the production of clean water; therefore, essentially they represent an opportunity cost. If they are disposed of in a landfill or by other conventional means, the products represent a treatment cost. If the harvested vegetation is allowed to naturally decompose to compost and the product is given away it still represents a cost savings to the wastewater aquaculture operator, because there will be no cost incurred for appropriate transportation and disposal. On the other hand, if there is a defined market for the by-product, given a slightly greater capital investment initially to upgrade the quality of the product by investing in approprite processing devices, such as an anaerobic digestor, then a greater economic return from the sale of the by-products to offset the treatment costs could be realized. Not only would users of wastewater aquaculture benefit from the recycling of fertilizer nutrients removed from the wastewater and added to the by-products; the by-product consumer would benefit as well. The use of composts as soil amendments, conditioners and fertilizers in the place of mineral fertilizers benefits the soil by not only increasing the organic matter content and water holding capacities, but also by reducing rainfall runoff and erosion impacts and evaporation from the soil surface.

8.4 Fiber

Harvested aquatic macrophytes cultured in wastewater aquaculture systems represent a potentially valuable fiber resource for use in many different consumer products. To date, the most popular fiber-use investigated for a wastewater aquaculture by-product has been the processing of water hyacinths for pulp and paper manufacturing. Unfortunately, the results of various studies consistently indicate that the water hyacinth has minimal application potential for paper production. Nolan and Kirmse(17) describe several characteristics of the water hyacinth that make it uneconomical to use as a pulp material or in blends. They include:

- Low freeness value in water hyacinth pulp and in pulp blends compared to pine kraft
- Very slow drainage compared to pine kraft pulp
- Low tear factor
- Low yield
- Poor appearance

Robinson et al.(12) attribute the poor paper manufacturing qualities of water hyacinth to its bulkiness and high water absorbency. They suggest the hyacinth may be more suitable in other products that would benefit from the plants high adsorbency characteristics, such as disposable diapers.

While the hyacinth has been demonstrated to be troublesome and uneconomical to use in paper manufacture, other aquatic macrophytes could prove to be more suitable for pulp production. Reeds, sawgrasses and cattails have been suggested as fiber sources for pulp. Through the use of the reed, Phragmites communis, Romanian manufacturers have addressed a significant aquatic reed problem and the decline in availability of wood for paper manufacture.(18) The reeds are harvested from the Danube River basin annually at a rate of about 125,000 tons and are converted to pulp for use in blending with wood pulp(14). Several paper products, fuels, synthetic fibers and fertilizers are some of the reported end-products that result from full utilization of reeds in Romania. Rudescu(18) recommends the utilization of sawgrasses in the same manner as *Phragmites communis*, due to their similar characteristics.

The National Academy of Sciences(14) assessment of the potential use of cattails (*Typha* spp.) as a source of pulp, paper and fiber is very optimistic. Though there has been no current assessment of pulp production potential or suitability for paper there is historical precedent for use of cattails in paper production. The National Academy of Sciences (NAS)(14) notes that books were produced in the eighteenth century that contain pages made from cattail paper. The assessment also notes that cattails are suitable as a weaving or caning material in mats, baskets, and furniture.(19) also mentions the application of the reed, *Scirpus* spp., for use in wicker furniture in West Germany.

8.5 Biogas Production

The bioconversion of wastewater aquaculture plant biomass to produce methane gas has been suggested as an appropriate by-product use for wastewater aquaculture systems. Depending on the scale of the facility, methane may or may not be produced in sufficient quantity to become a saleable by-product. In certain cases, the volume produced may only be sufficient to heat digesters to optimum methane production temperatures or possibly for a few other on-site uses. Digester sludge, however, may be a marketable by-product of the anaerobic digestion process as it can be used as a fertilizer product.

Methane production in anaerobic digestion processes. can be influenced by a variety of factors of which, the C:N ratio of the digester material is most important. Wolverton et al.,(20) reports that water hyacinths maintain a desirable C:N ratio of 23:1 for maximum methane production. Other factors such as lignin content also affect the suitability of a given plant material for anerobic digestion to produce methane gas. The lignin content of plants is important in that this particular cellulosic compound is very difficult to biodegrade and will affect the quantity of methane production. While water hyacinths have a low lignin content, generally, most marsh plants have a higher lignin concentration and are less suitable.(21)

The anaerobic filter process has been developed for high rate anaerobic digestion using water hyacinths at the National Space Technology Laboratories (NSTL) in Mississippi.(22) In bench scale studies using this method, maximum methane yields of 3.17 ft^3/lb dry weight for water hyacinths and 2.34 ft^3/lb dry weight for water pennywort were achieved. During this study, it was also found that the anaerobic filter performed most efficiently after several uses. Temperature during the experiments was maintained by an incubator at 37°±1°C. In full scale operation, temperature may prove to be a significant constraint to this bioconversion method. Conventional digesters lose heat through several different pathways, through the walls, floor and roof of the digester, which will have to be compensated for in digester heating. The energy expenditure in maintaining the digestor temperature may offset the energy gain in methane production. In addition, the methane produced in the digestor is not readily useable, and contains carbon dioxide, hydrogen sulfide and other contaminants which must usually be removed prior to burning the gas.

In summary, the initial outlook for bioconversion of wastewater aquaculture plant biomass to methane gas may have been too optimistic in terms of quantity and widespread applicability to wastewater aquaculture systems. The seasonal variation in plant biomass production in different climates will also affect anaerobic digestion applications. Low-temperature gasification (pyrolysis) has been suggested as an alternative to anaerobic digestion for energy production, but extensive data on this method has not yet been made available for evaluation.(23)

8.6 Feeds and Feed Supplements

The potential for aquatic plant biomass processed for use as animal feeds and feed supplements is very optimistic. Nutritionally, several aquatic plants investigated thus far have been found comparable to terrestrial plants commonly used for roughage in ruminant diets. While much research again has been centered around the water hyacinth, additional investigation is necessary for other aquatic plant species to determine their value in livestock feed applications. Experience in removing water through pressing, solar drying and other methods has indicated that dewatering is a technical and economic constraint to utilizing wastewater aquaculture plant biomass for animal feeds and feed supplements.

The nutritional value of several species of aquatic plants that have been grown in wastewater aquaculture systems have been evaluated to assess suitability for use as animal feeds and feed supplements. In addition, fish harvested from wastewater aquaculture systems may also have value as fish meal similar to menhaden meal which is currently used as a protein supplement in livestock feeds.

Much of the published research pertains to the water hyacinth and its nutritional value, acceptability (processed and unprocessed) and its value in silage for livestock feed. And, it can be concluded that water hyacinths are suitable feed supplements (dried or ensiled) for ruminant animals. Possible constraints to using water hyacinths in cattle or sheep diets involve mineral content, palatability, ash content, and protein content.

Table 8.1 shows the mineral content reported by Easley and Shirley(24) for water hyacinths. The concern over minerals involves the possibility of mineral imbalances which might be caused due to the relatively high degree of these substances in dried, pressed and ensiled water hyacinths compared to conventional livestock feeds. Palatability problems arise when cattle are fed dried, ensiled water hyacinths alone. However, when hyacinths were ensiled in combination with citrus pulp or molassas, the feed was readily accepted by cattle.(12) High ash content in hyacinth feeds appears to reduce gross intake by livestock and therefore could affect growth rate. The protein content of water hyacinths has led some researchers to conclude that supplemental protein is necessary in livestock diets where processed water hyacinths are used.(12)

Several species of the duckweed family (Lemnaceae) have also been analyzed for their protein content to assess the potential of using duckweed species in animal feeds. While species of Lemna, Spirodela and Wolffia have not been as intensively investigated as the water hyacinth in this regard, initial studies have indicated that they are acceptable as animal feed sources. Culley and

Table 8.1

CONCENTRATION OF MINERAL FEED NUTRIENT ELEMENTS REPORTED BY EASLEY AND SHIRLEY FOR WATER HYACINTHS(24)

Element	Average	High	Low
	Percent, Dry Basis		
Calcium	2.2	2.7	2.0
Phosphorus	0.50	0.66	0.17
Potassium	4.1	6.4	1.0
Magnesium	0.59	0.64	0.52
Sodium	0.94	1.20	0.62
	mg/kg, Dry Basis		
Iron	1,701	3,183	522
Copper	12	30	7
Zinc	43	71	30
Manganese	142	227	106
Chromium	3.2	10.6	-0-

Epps(25) characterized the positive animal feed aspects of the various duckweed species to include:

- relatively easy harvesting
- low fiber and lignin content
- high mineral absorptive capacities
- few pests
- extended growing season

Experimentation with duckweed feeding trials has demonstrated that duckweed use in poultry diets actually increased growth rates as compared to conventional feeds.(26) Swine have also been fed unprocessed duckweeds successfully. The nutritional analysis of domestic wastewater-grown Spirodela oligorhiza is provided in Table 8.2 as compared to several conventional animal feeds.

A vitamin evaluation of the pondweed (Potamogeton foliosis) harvested from the Deshler, Ohio sewage treatment lagoon was conducted to assess its value as a vitamin source in swine and poultry feeds.(26) The evaluation indicated that the sewage lagoon biomass vitamin content compared favorably to conventional feeds, as demonstrated in Table 8.3.

In general, the greatest constraint to the use of aquatic plants as feed supplements has been the excessive processing requirements which often involve costly drying and additives to amend the final product.

8.7 Harvesting and Processing Wastewater Aquaculture Biomass

If by-product utilization is considered for an APU, efficient and economical by-product harvesting and processing methods must be established. A wide variety of harvesting techniques have been used in APUs. Generally, the methods of harvest are influenced by the following variables.

- type of biomass harvested
- size and configuration of APU
- amount of biomass present and desired rate of removal
- skill of available operating personnel

Table 8.2

NUTRITIONAL ANALYSIS OF WASTEWATER GROWN *SPIRODELA OLIGORRHIZA* IN COMPARISON WITH SEVERAL ANIMAL FEEDS(25)*

Feed Type	Proportion of Component %					
	Protein	Fat	Fiber	Ca	P	Ash
Duckweed*** (*Spirodela oligorrhiza*)	28.5**	5.5	11.8	1.3	1.0	17.7
Alfalfa leaf meal	20.0	3.5	21.0	1.45	0.27	10.5
Coastal Bermuda grass (dehydrated)	14.0	2.0	28.0	0.50	0.20	6.0
Corn (yellow)	8.8	3.8	2.5	0.01	0.25	1.5
Cottonseed meal	41.0	4.0	13.0	0.15	1.20	6.5
Milo maize	9.0	2.5	2.7	0.02	0.27	1.7
Oats	12.0	4.0	12.0	0.10	0.33	3.5
Peanut meal and hulls (expeller)	45.5	6.0	12.0	0.15	0.55	5.8
Soybeans	37.0	18.0	5.0	0.25	0.58	4.7
Soybean meal (expeller)	42.0	3.5	6.5	0.20	0.60	6.0
Wheat bran	14.5	3.0	11.0	0.10	1.15	7.0

* Adapted from Culley & Epps (1973)(25)

** Crude Protein

*** Cultured in Domestic Wastewaters

Table 8.3

COMPARISON OF SEWAGE LAGOON BIOMASS VITAMIN CONTENT WITH OTHER FEEDS (26)

Vitamins	Feed Source (mg/kg dry weight)					
	Lagoon Biomass	Alfalfa	Barley	Sugar Beet	Corn	Soybean
Biotin	0.36	--	0.20	--	0.05	0.32
B_{12}	0.10	--	--	--	--	--
Choline	1020.00	1550.00	1030.00	829.00	550.00	2743.00
Niacin	30.00	41.90	57.40	16.30	20.00	26.80
Pantothenic Acid	13.18	20.90	6.50	1.50	5.00	14.50
Total B_6	1.35	6.50	2.90	--	5.0	8.0
Riboflavin	19.81	10.60	2.0	0.70	1.10	3.30
Thiamine	5.00	3.00	5.10	0.40	--	6.60

- compatibility with end product utilization scheme
- cost

The processing requirements of animals and plants harvested from APUs are necessarily determined by the end-product desired.

8.6.1 Aquatic Plant Harvesting and Processing

Aquatic plant harvesting methods have been studied extensively, chiefly to develop methods to combat nuisance growth of aquatic weed in waterways and lakes. The results of research efforts have led to the development of water-based mechanized harvesting equipment to remove vegetation from the water and transport it to shore. The use of floating or barge-mounted aquatic plant harvesting machinery is applicable for APUs where configuration does not allow retrieval from land-based cutting and conveyor equipment.

Land based harvesting systems can be utilized for APUs systems that provide sufficient land access to the unit. Several types of floating and land based harvesting eequipment are commercially available. The water hyacinth culture basins at Walt Disney World, Florida are designed to facilitate a land-based harvesting, technique from the sides of concrete channels 360' x 29'.(27) During harvesting the plants are manually guided with a hook to a conveyor attached at the side of the channel. From the conveyor, the plants are passed through a flail chopper, and the chopped plants are then piled. A similar system that can be used in lagoons with broad surface areas uses a pusher boat to guide hyacinths to a conveyor which is 1.52 m wide and 8.53 m long and has a capacity of 9.2 tons/hr.(29) A drag line bucket arrangement has also been used to harvest water hyacinths and was found to provide simple and flexible continual operation. Stewart(29) reported the use of a pump with a cutter element for hyacinth harvesting with a harvest rate potential of 2 tons/hr. Dinges(30) has proposed constructing harvesting platforms in hyacinth basins to support harvesting machinery. The platforms are normally submerged but water levels are lowered during harvesting to permit access by harvesting equipment.

Generally, aquatic harvesting equipment is a significant capital investment. A practical solution to help mitigate the cost of the equipment might be to develop harvester-sharing arrangements with local organizations (state, county or local lake associations) that use aquatic weed harvesters to control overgrowth in waterbodies. Such a situation exists in Plant City, Florida, where the state loans its aquatic weed harvester to the treatment plant periodically to harvest water hyacinths from their polishing ponds.(33)

Duckweed is relatively easier to harvest than water hyacinths because of small size and formation of dense floating mats. Commercially available screening and skimming devices can be used for this purpose.

Other types of aquatic vegetation that are submerged or emergent can be harvested through a variety of techniques that are both manual and mechanical. Reeds, cattails and other emergents can be mechanically harvested with mobile equipment or manually harvested with implements such as a scythe. Submerged aquatic vegetation can be harvested mechanically with harvesters fitted with cutter bars.(31)

Subsequent to harvesting the aquatic plants, processing usually begins with chopping or shredding the plants to reduce volume for easier handling and transport. The amount of further processing is determined by the end product desired. After chopping, plants destined to be used as soil amendments can be applied directly to the soil to take advantage of high moisture content, or piled and allowed to decompose. Chopping and blending into a slurry is required for plants which are to be used in an anaerobic digester to produce methane gas.(22) Further processing for biogas production involves labor inputs in monitoring and controlling the digester and the remaining accumulated sludge. Chopping is also required for those plants destined for pulping processes used in paper manufacture.

Several other by-product utilization schemes including use in animal feeds and feed supplements require the drying of aquatic vegetation. Drying beds similar to those used for sludges resulting from conventional treatment processes can be used, however, they require land adjacent to the already land-consumptive treatment plant. There have also been experiments with solar greenhouse dryers.(32) Several different types of presses have also been used to reduce water content. However, after pressing, moisture content is still significant and the extracted liquid, which contains solids, nitrogen, and phosphorus, becomes a waste which must be recycled through the APU or otherwise used. Additional drying techniques which follow pressing have involved rotary dehydrators, fixed or traveling bed dryers and air-agitated dryers.(12) Ensiling dried aquatic vegetation with sugarcane, molasses, corn hulls, citrus pulp, and other substances has been practiced to improve palatability to livestock.(12)

8.8 Harvesting and Processing Aquatic Animals

The technology for aquatic animal harvesting has been well-developed by the clean water aquaculture industry and can be applied to the harvest of organisms cultured in APUs. As with aquatic plants, the equipment and harvesting techniques used for removal of aquatic species are again dictated by the type of animal and the size and configuration of the basin in which they are cultured. The devices used to harvest fish in lagoon-type systems include seine nets, boom lift nets and others.(4) In recovery arrangements, fish can be harvested by draining the ponds and using dip nets, or by culturing in cages. Other animals such as clams have been cultured in trays stacked in the raceway on racks.(4) Harvesting can be accomplished by lifting the rack from the raceway.

The processing requirements of aquatic animals intended for human consumption are not delineated here because current pulic health regulations prohibit this practice when the water used in the culture of aquatic organisms is derived from wastewater sources. Other processing steps that can be used involve anaerobic digestion of fish to fertilizer products or protein supplements in animal feeds as discussed previously in this chapter.

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